Update on HIDRA Activities

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NPRE ILLINOIS
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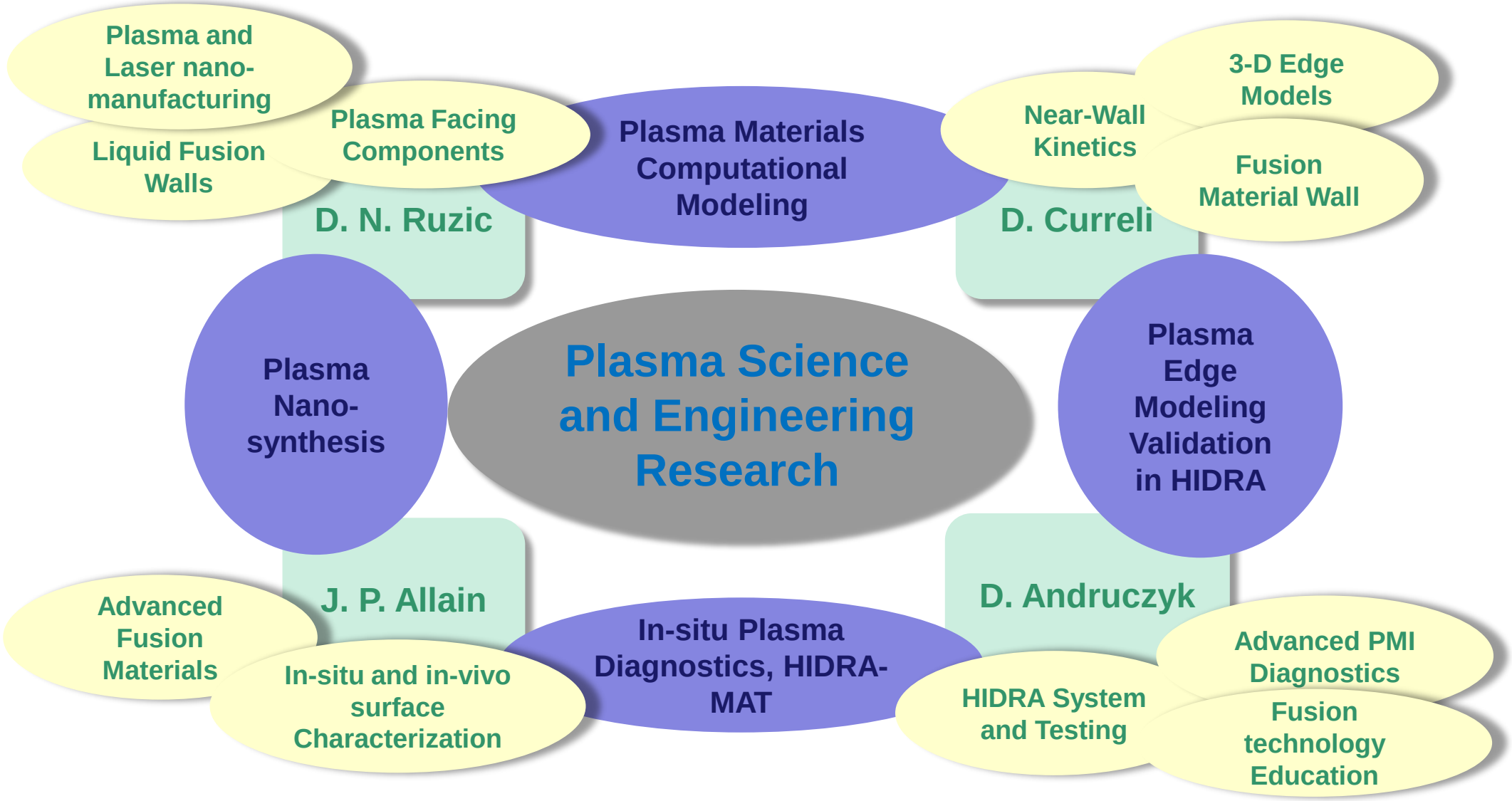
Plasma Research at the Center for Plasma Material Interactions



Outline

HIDRA Overview

HIDRA Control

Field Line Mapping

HIDRA Diagnostics

HIDRA-MAT

Liquid Lithium Limiters

MEME

Future Work

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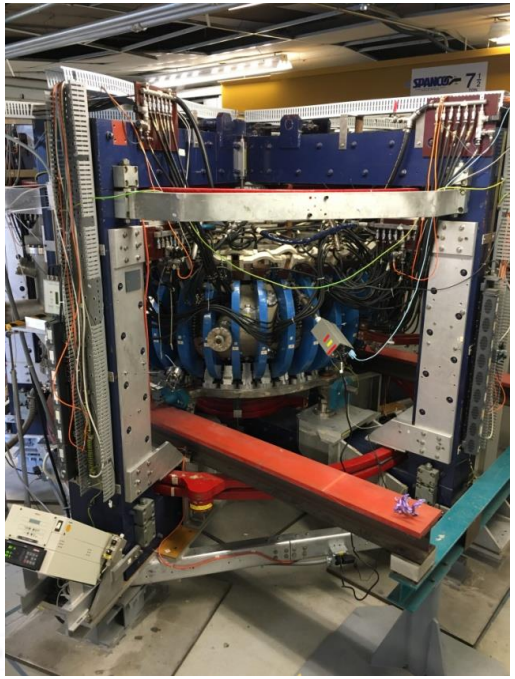
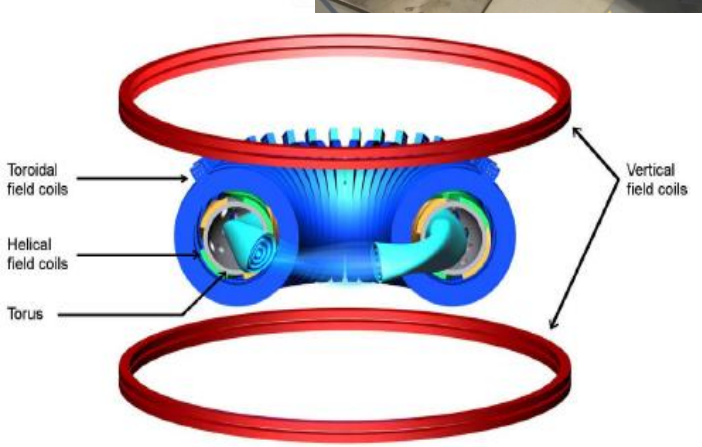
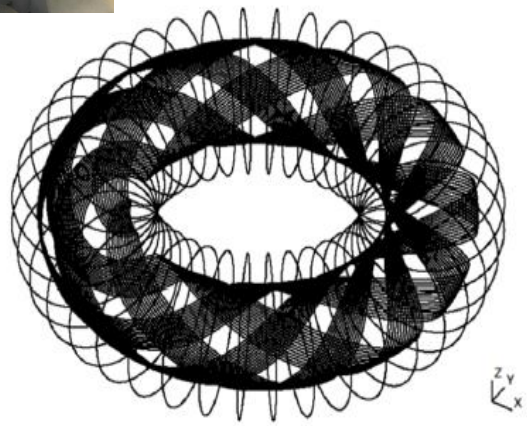
Future Work

Hybrid Illinois Device for Research and Applications (HIDRA)

- Stellarator as well as tokamak capabilities
  - Vessel splits in half, easier access to install larger components
- Magnet configuration
  - 40 toroidal coils
  - 4 helical coils
  - 2 vertical field coils
  - 84 ports, 6 sizes accessible
- Stellarator operations in Greifswald as WEGA
  - R_0 = 0.72 m
  - r = 0.19 m
  - B_0 = 0.087 – 0.5 T
  - f_{gyr} = 28 GHz, P_{gyr} = 10 kW cw, 40 kW pulsed
  - f_{mag} = 2.54 GHz, P_{mag} = 6 kW + 20 kW
  - $n_e < 1 \times 10^{18}$ m^{-3}
  - **T_e = 5 – 25 eV**
  - **t_{pulse} < 60 min**
  - $\Gamma = 1 \times 10^{22}$ m^{-2}s^{-1}

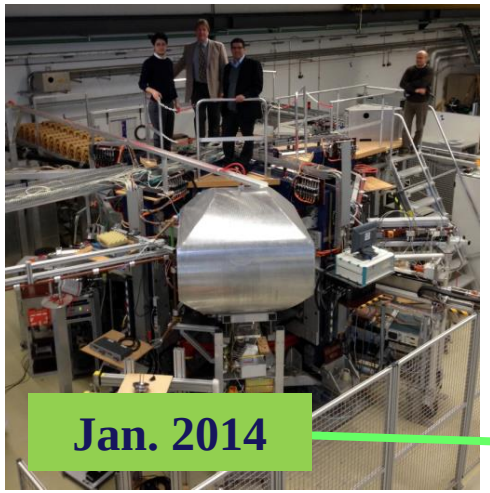




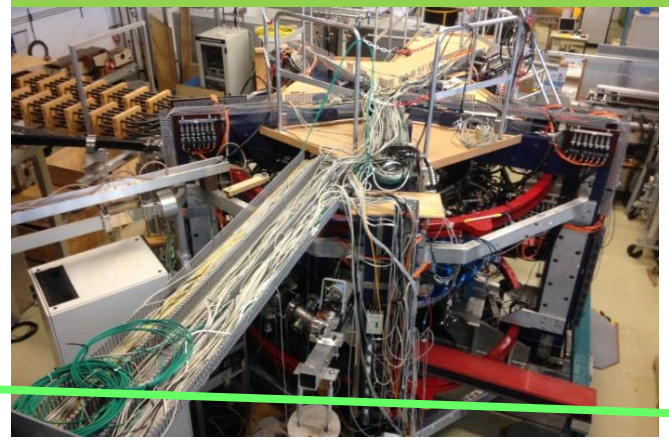


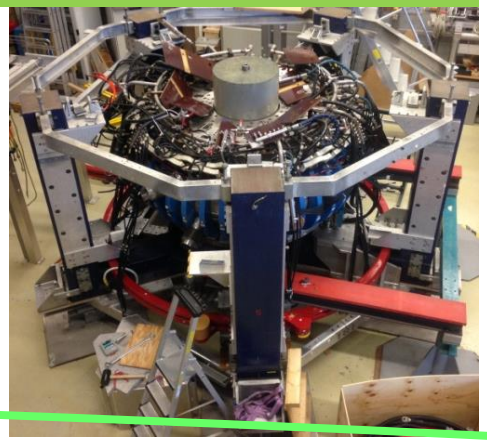
D. Andruczyk, *et al.*, Fusion Sci. Technol. **68** (2015) 497

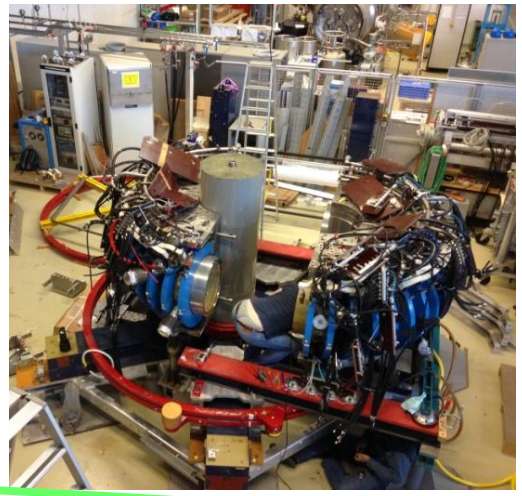
Greifswald to Illinois



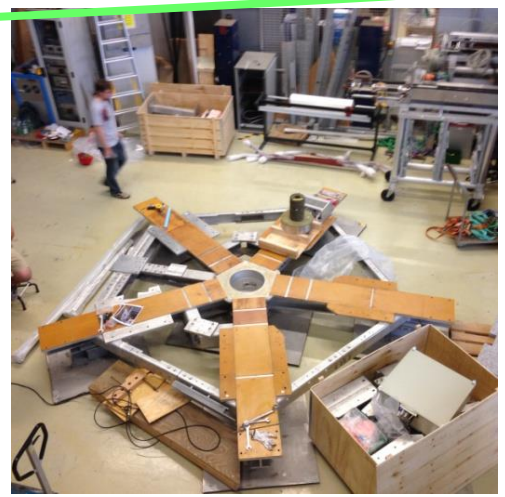
July 2014 – Start Disassembly of WEGA







Sep. 2014 – Continue Disassembly WEGA → HIDRA → Packing and Shipping

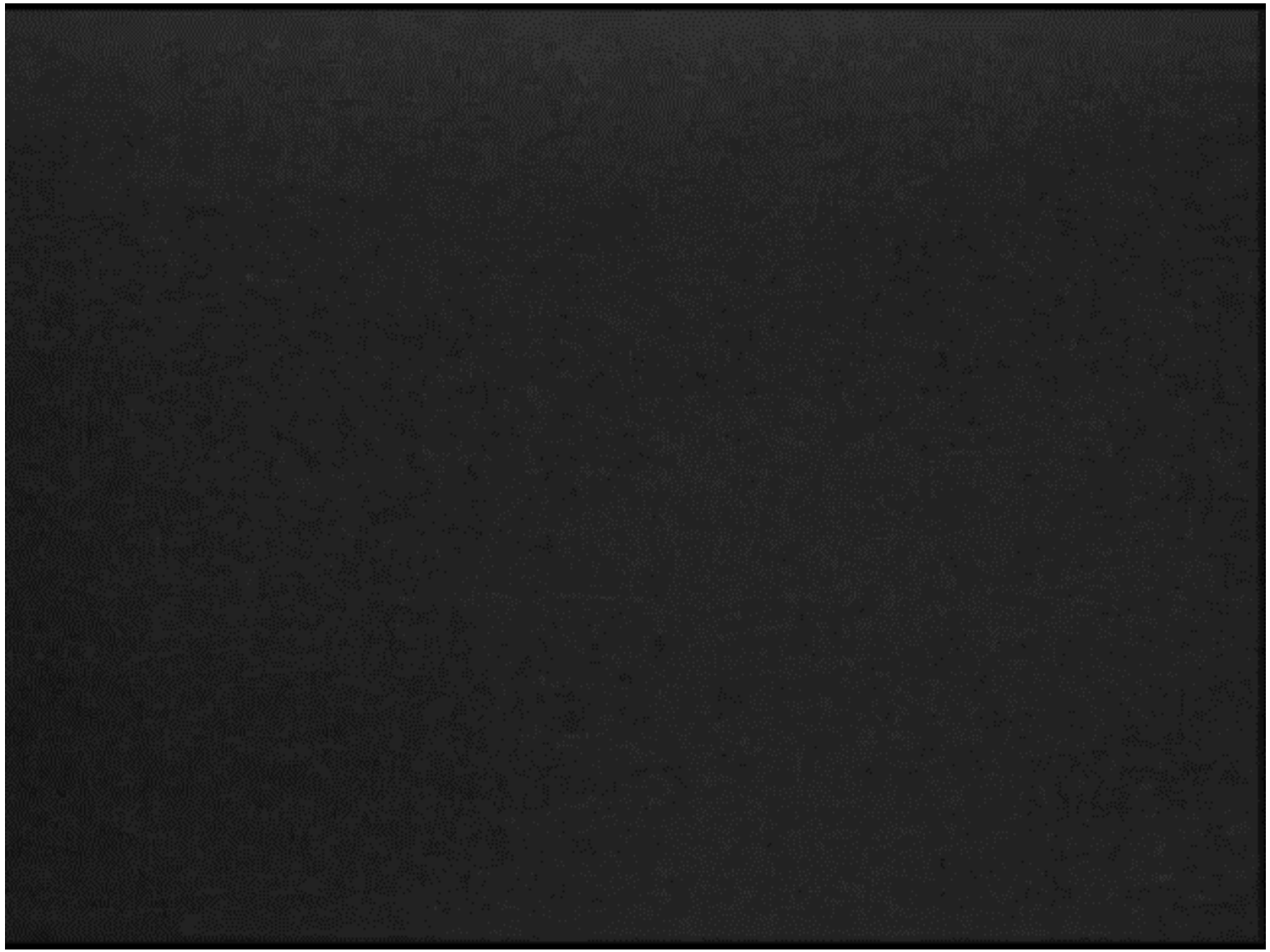


First Time a Fusion Device has been Shipped from Europe to USA

- November 2014 WEGA arrives at University of Illinois, re-named HIDRA
  - Hybrid Illinois Device for Research and Applications
- Assembly began straight away, within 2 weeks the large heavy components are installed
- External systems installed
  - Cooling
  - Heating
  - Vacuum
  - Electrics and Magnetics
  - Control systems
  - Safety
  - Diagnostics

HIDRA arriving in Illinois, November 2014

Video of the Assembly of HIDRA



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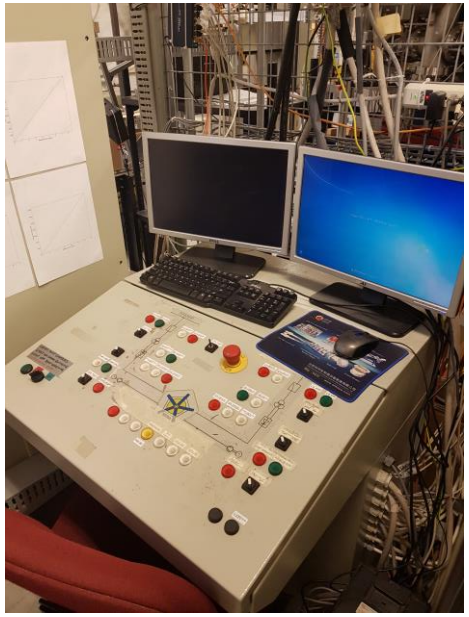
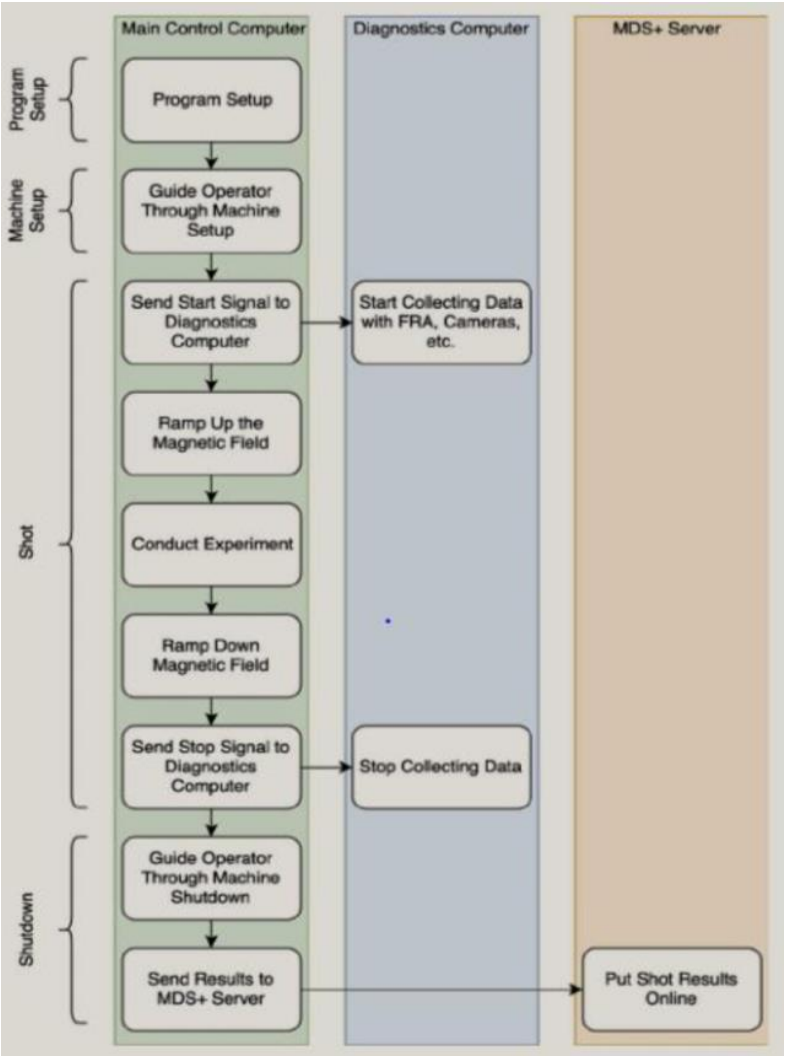
Controlling HIDRA

- HCS contains three main Components:
  - Main Control Computer
  - Diagnostics Computer and
  - MDSplus server.

D. Johnson, *et al.*, Fusion Eng. Design **128** (2018) 215

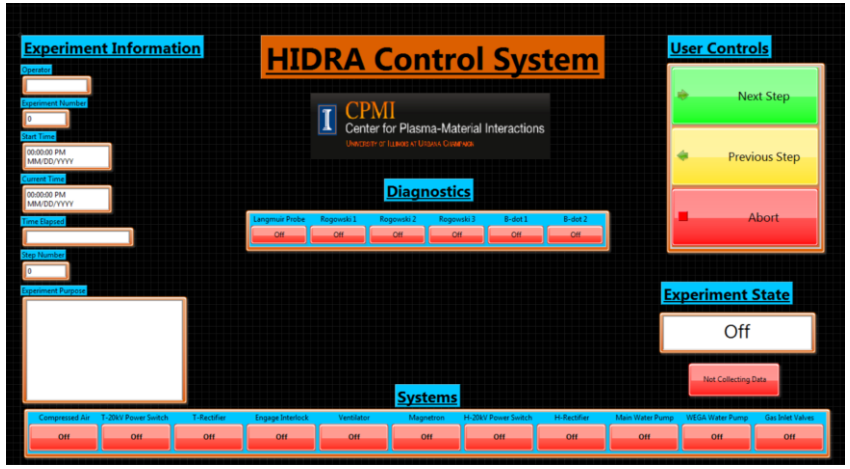




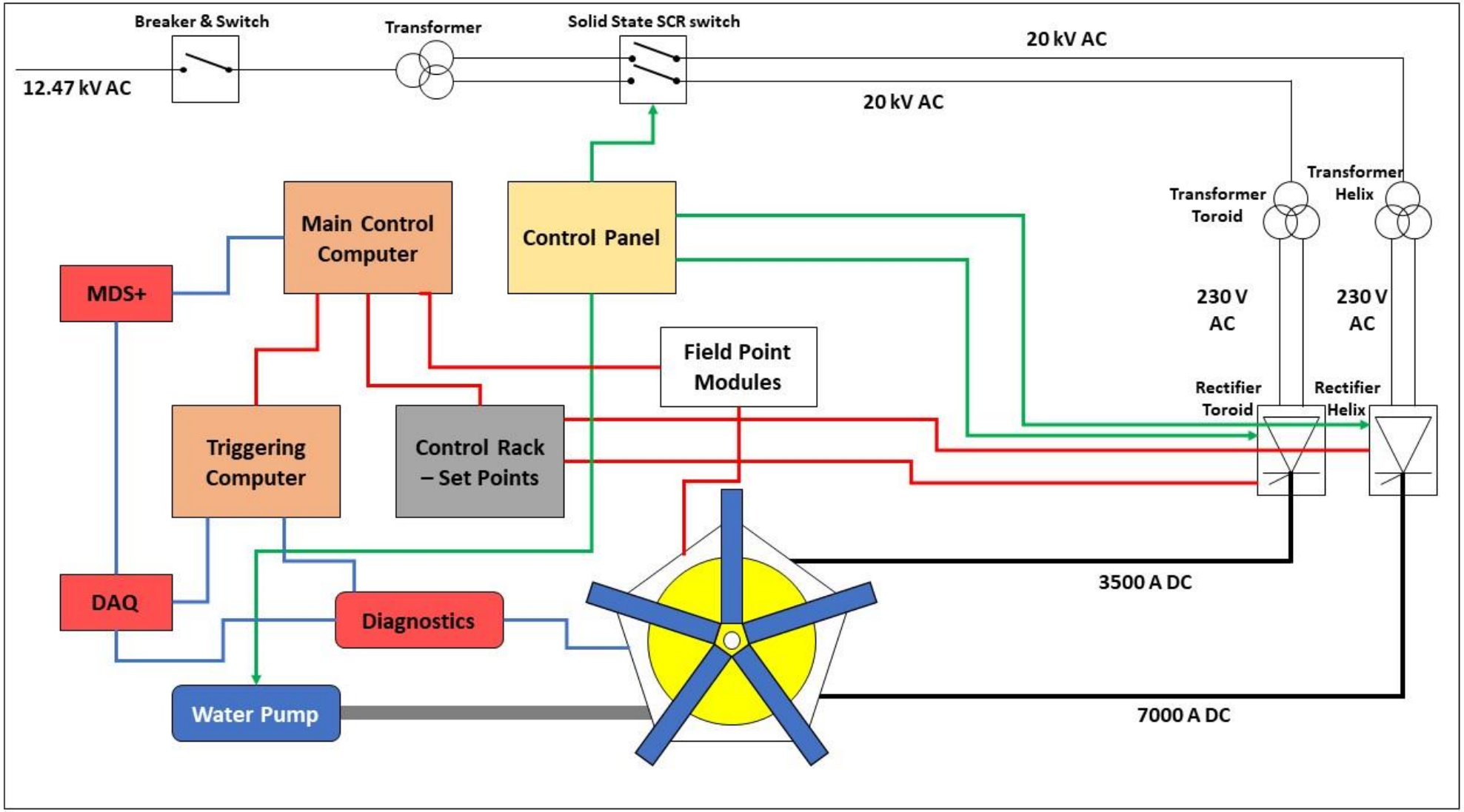
- LabVIEW code runs in four parts: Program Setup, Machine Setup, Shot and Shutdown

- During a shut the HCS communicates with the DC and the MDSplus server.

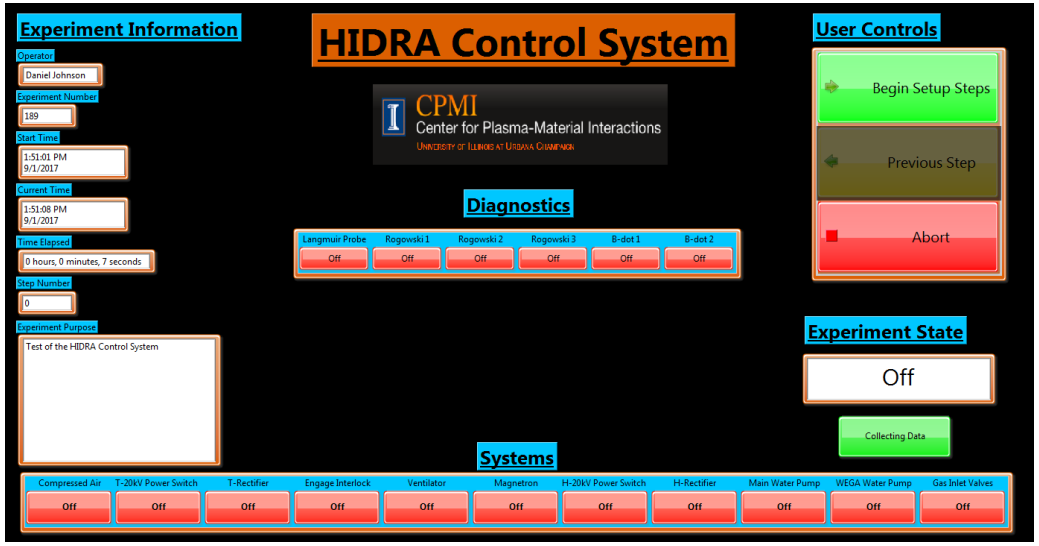
- After a run each shot is stored in a unique data set.

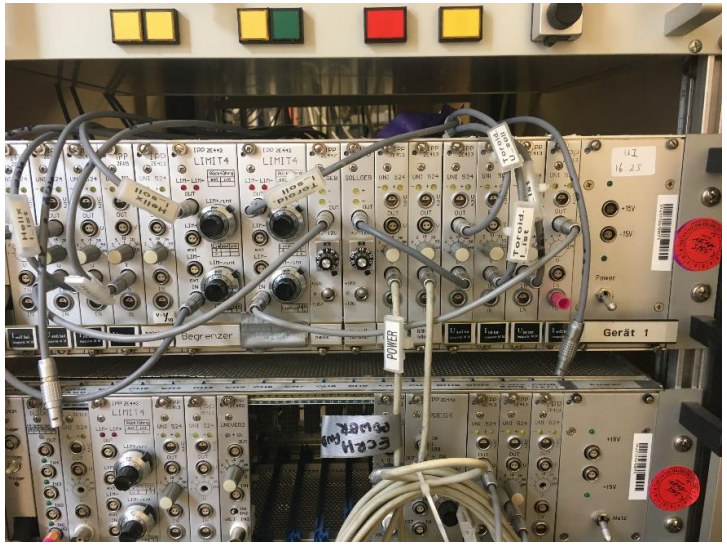


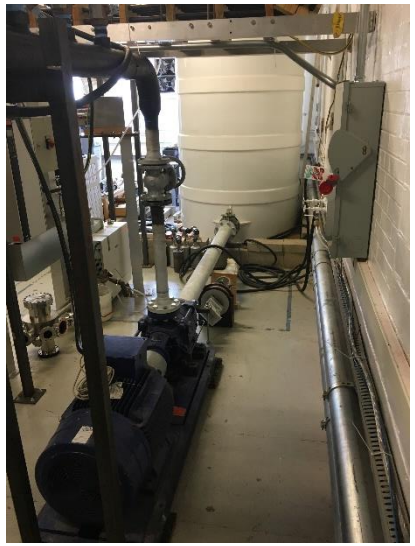
HIDRA Systems



HIDRA Systems







HIDRA Control : Work Flow

- User inputs time delay before oscilloscope starts collecting data
- Python code is run and waits for a signal from the main computer
- Main control computer runs shot and sends signal to trigger system
- Signal is received by the trigger system starting the time delays
- Oscilloscope starts collecting data once time delay finishes
- After the shot is finished the data is sent to the MDSplus server

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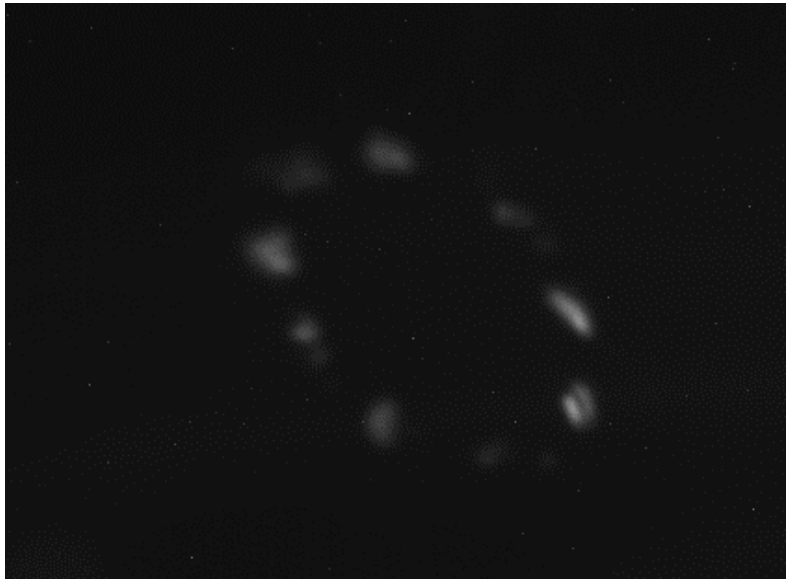
Field Line Mapping – Experimental Setup

- A ZrO2 painted rod was positioned at a toroidal angle of 216 and swept through the vacuum vessel
  - Allows detection of electrons fired from electron gun
  - Electron gun positioned at various radial positions
  - Measurements taken both with and without ±12A vertical field



- The Starlight Xpress HX916 CCD was used to capture the electron traces

- The flux surfaces were built up by superimposing the images for each individual iota configurations

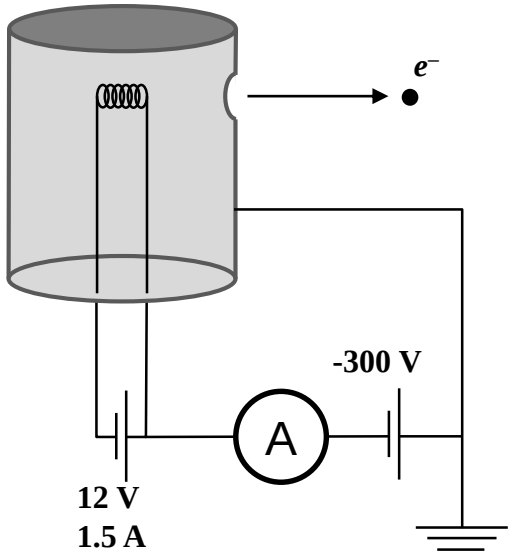
$$\iota = 0.1\left(\frac{I_H}{I_T}\right)^2$$

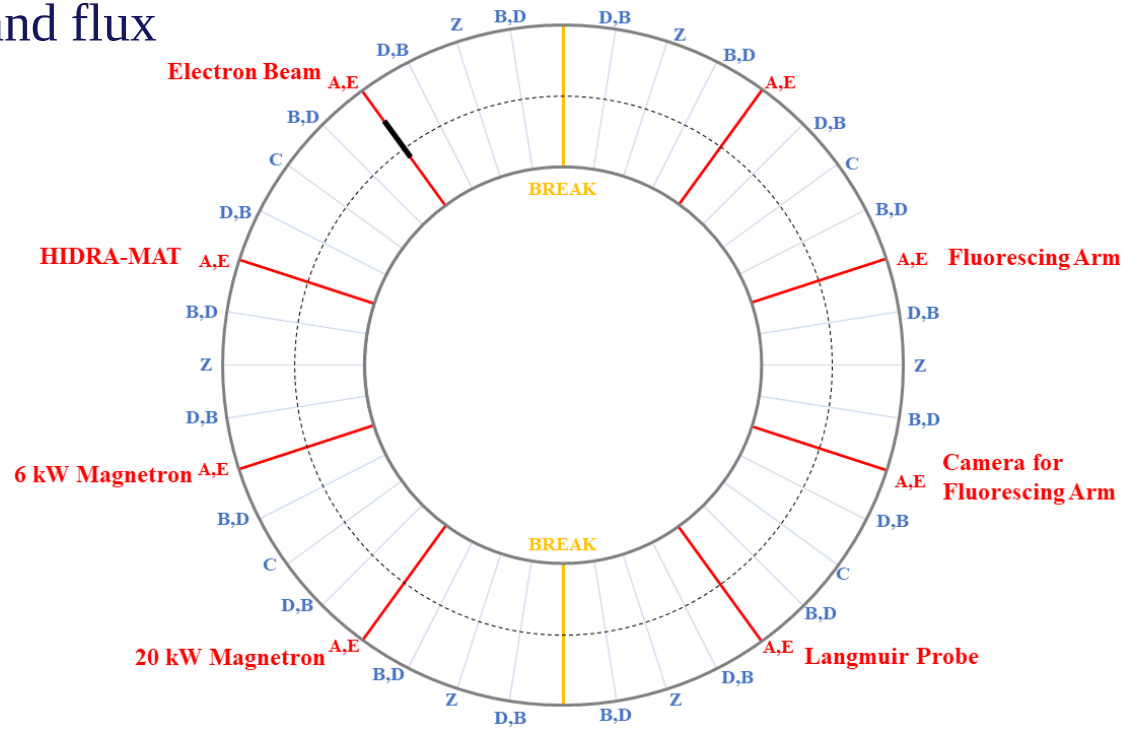
	$I_T\ (A)$	$I_H\ (A)$
$\iota = 1/3$	−486	900
$\iota = 1/4$	−486	790
$\iota = 1/5$	−486	710

R. Rizkallah, *et al.*, IEEE Trans. Plasma Sci. **48** (2018) 2685

e^- beam and Mesh for Field Mapping

- A simple electron gun has been designed to do magnetic field and flux line mapping
- Based on the filament from a halogen lamp
  - 12 V – 15 V and up to 2 A for emission voltage and current
  - Up to –300 V for the bias to extract the electrons
- Electron will follow a magnetic field line from a set position.
  - Visualize with cameras
  - Flux lines eventually will be visualized via a fluorescing moving arm.

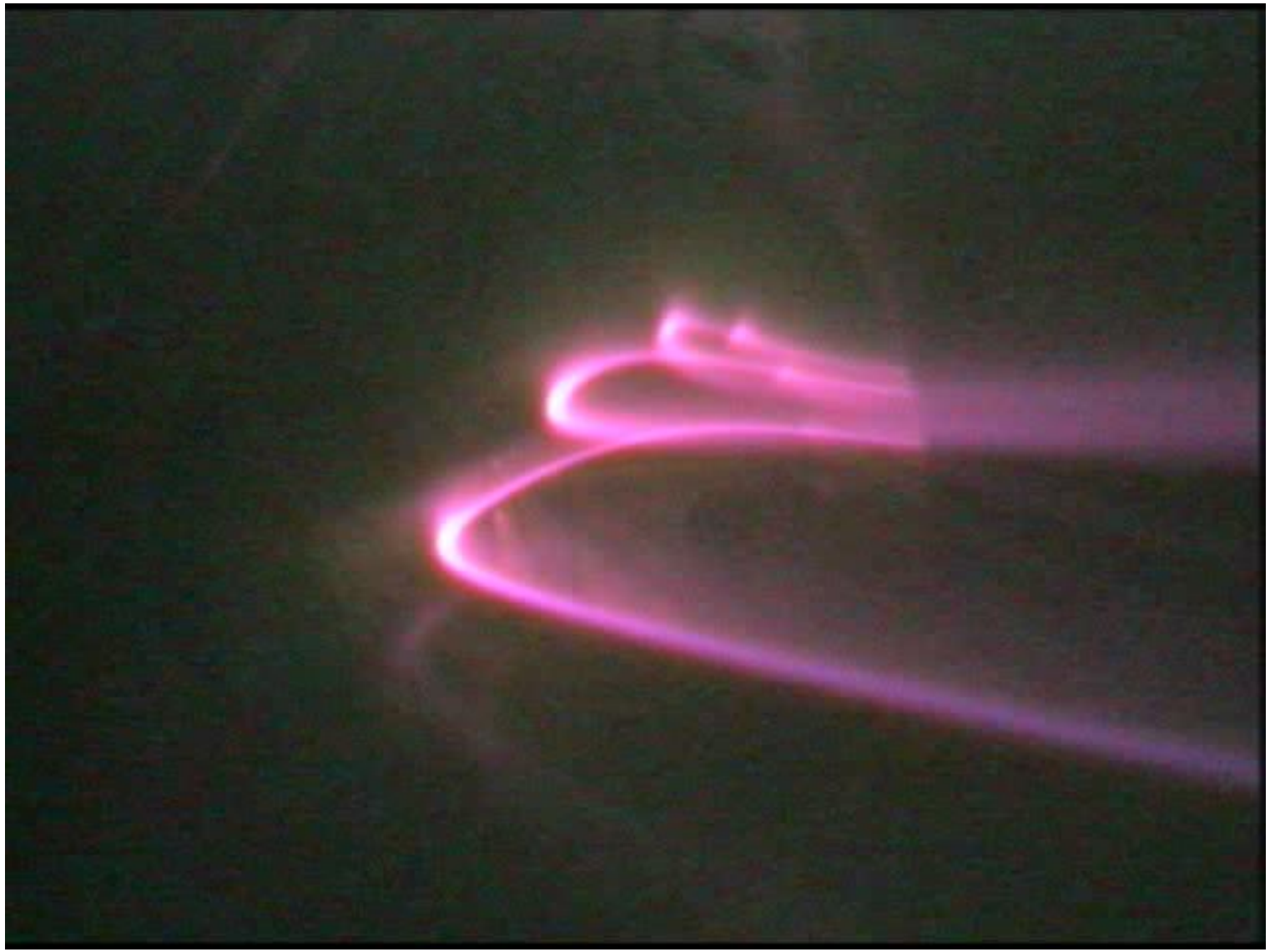




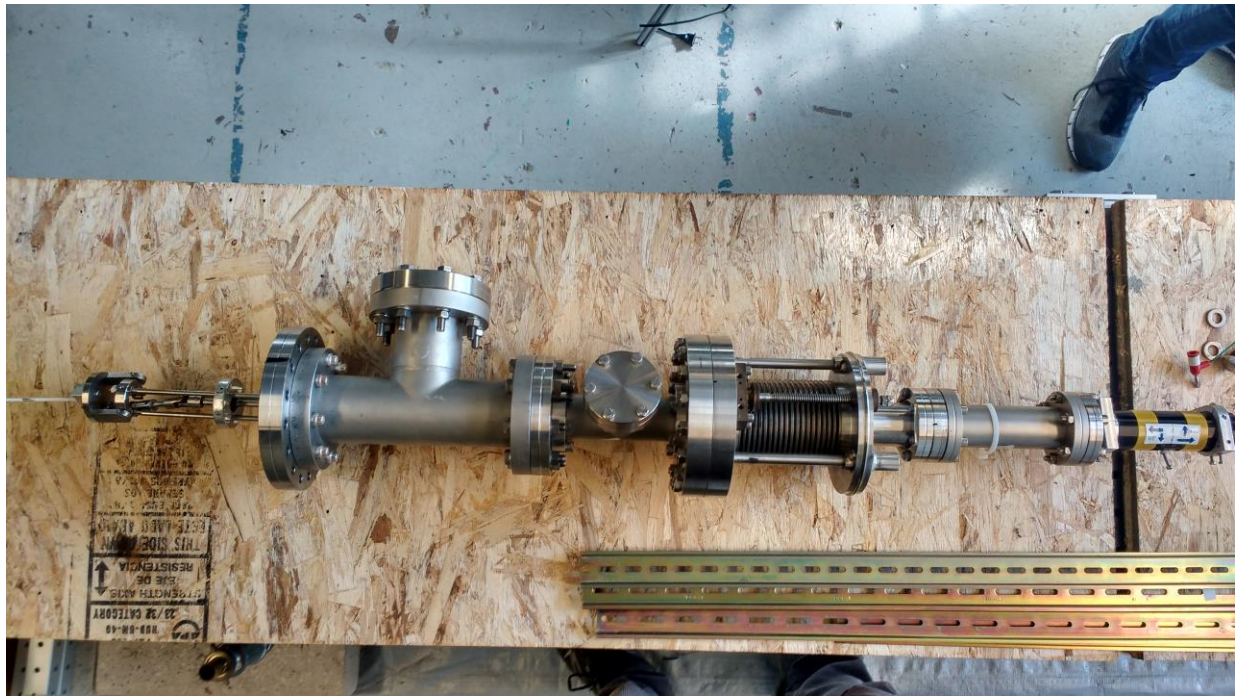
- Electron gun is mounted on a reciprocating probe arm
  - Extended all the way to the high field side wall to the low field side wall
  - Scans from the center to the 10 cm from the center of vessel (R_0 = 0.72 ⟶ 0.82 m)
- Three cameras are used to visualize the electron beam.
- Currently the parameters of beam, pressure, gas type and B field used

Field Line Mapping

Electron Beam in HIDRA



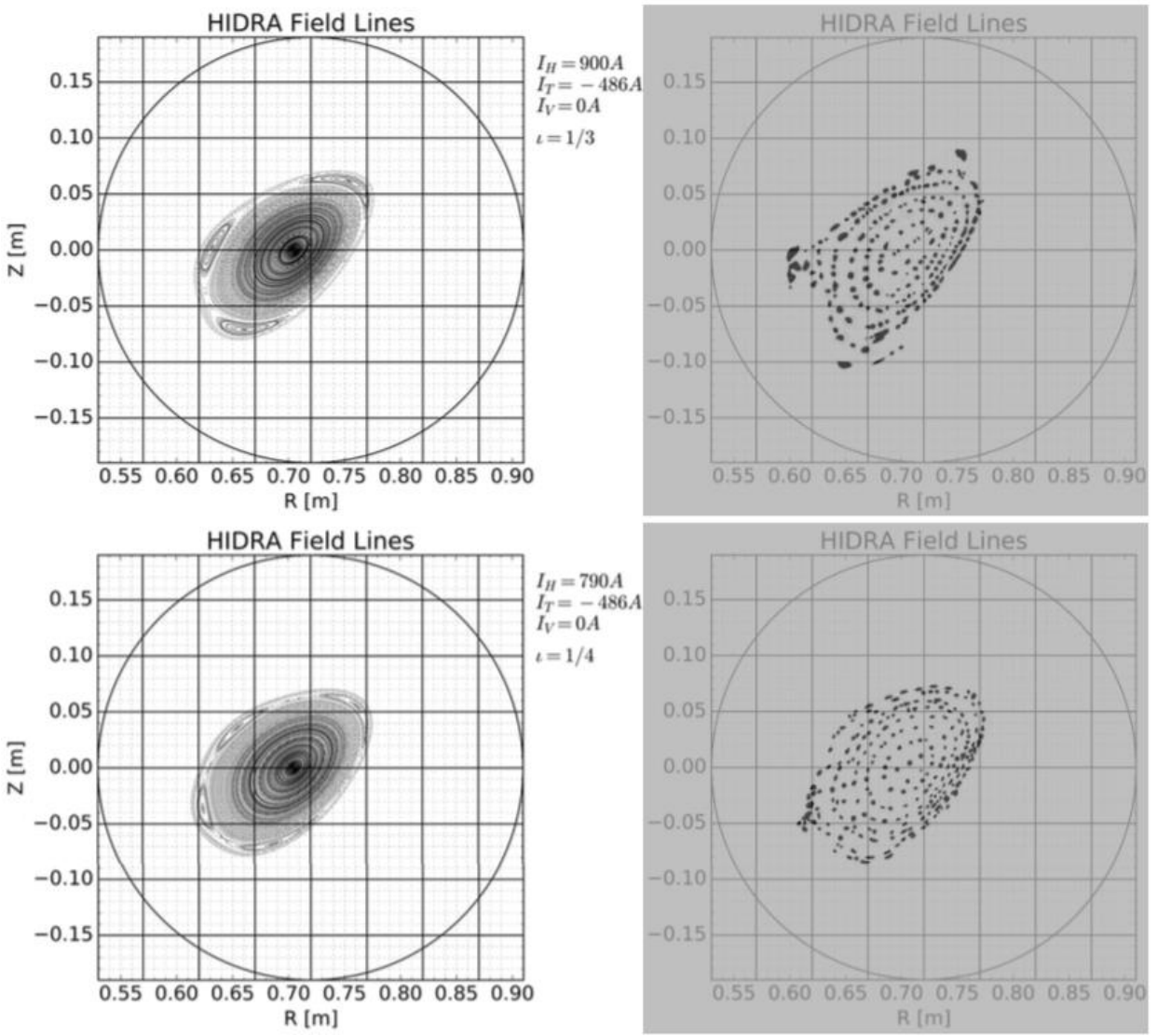
Fluorescing Arm for Magnetic Flux Line visualization



Field Line Mapping

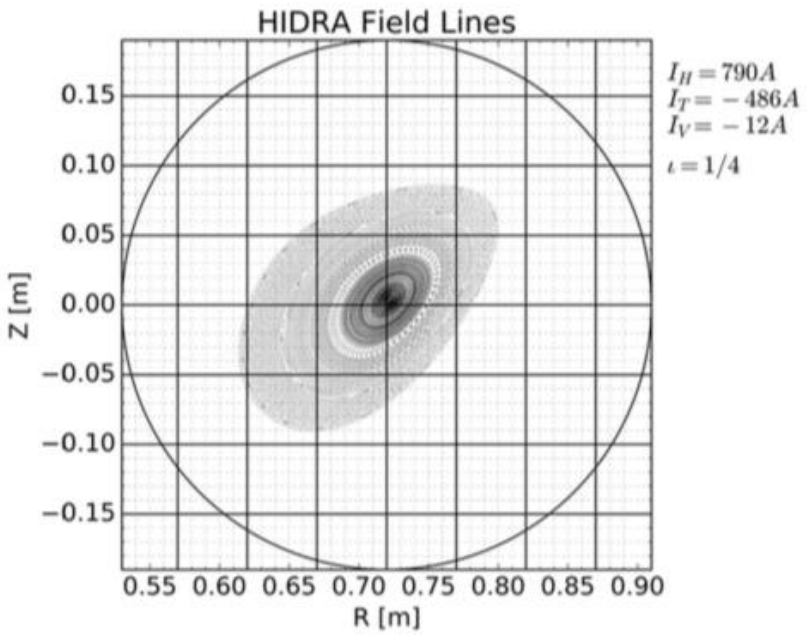
- The CCD captured images were processed and filtered before building up the composite image
- The two images agree in terms of:
  - The shape of the plasma
  - The island location
  - The position of the magnetic axis
- This suggests that the error field on HIDRA is the same that was seen on WEGA
  - Possibly due to a relative shift between the plasma vessel and the attached helix and toroidal field coils

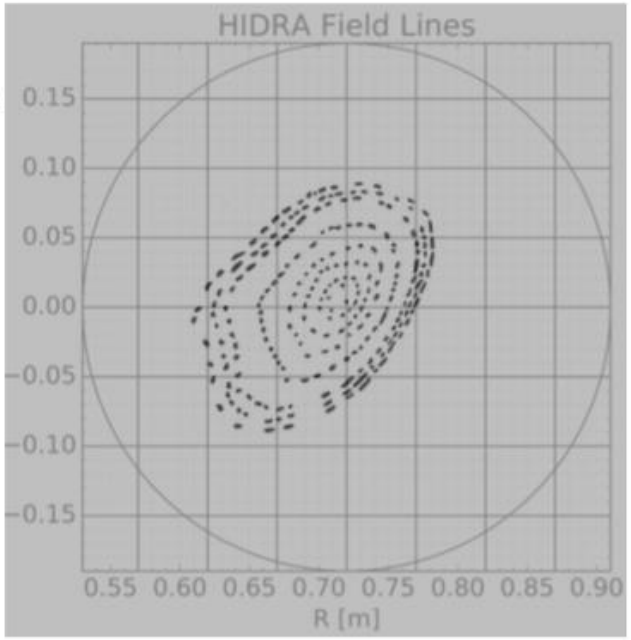
Magnetic axis location with VF = 0A		
	$R\ (m)$	$Z(m)$
$\iota = 1/3$	0.7052	$-1.287E-04$
$\iota = 1/4$	0.7052	$-1.305E-04$
$\iota = 1/5$	0.7052	$-1.360E-04$



Field Line Mapping – Vertical Field Effects

- When the vertical field is included the islands are pushed towards the magnetic center
- Plasma configurations without $m = 1$ rational resonances are possible
- Shifts the Plasma radially (around 2cm)





Radial magnetic axis location (m)		
	$VF = +12A$	$VF = -12A$
$\iota = 1/3$	0.6867	0.7215
$\iota = 1/4$	0.6816	0.7256
$\iota = 1/5$	0.6757	0.7297

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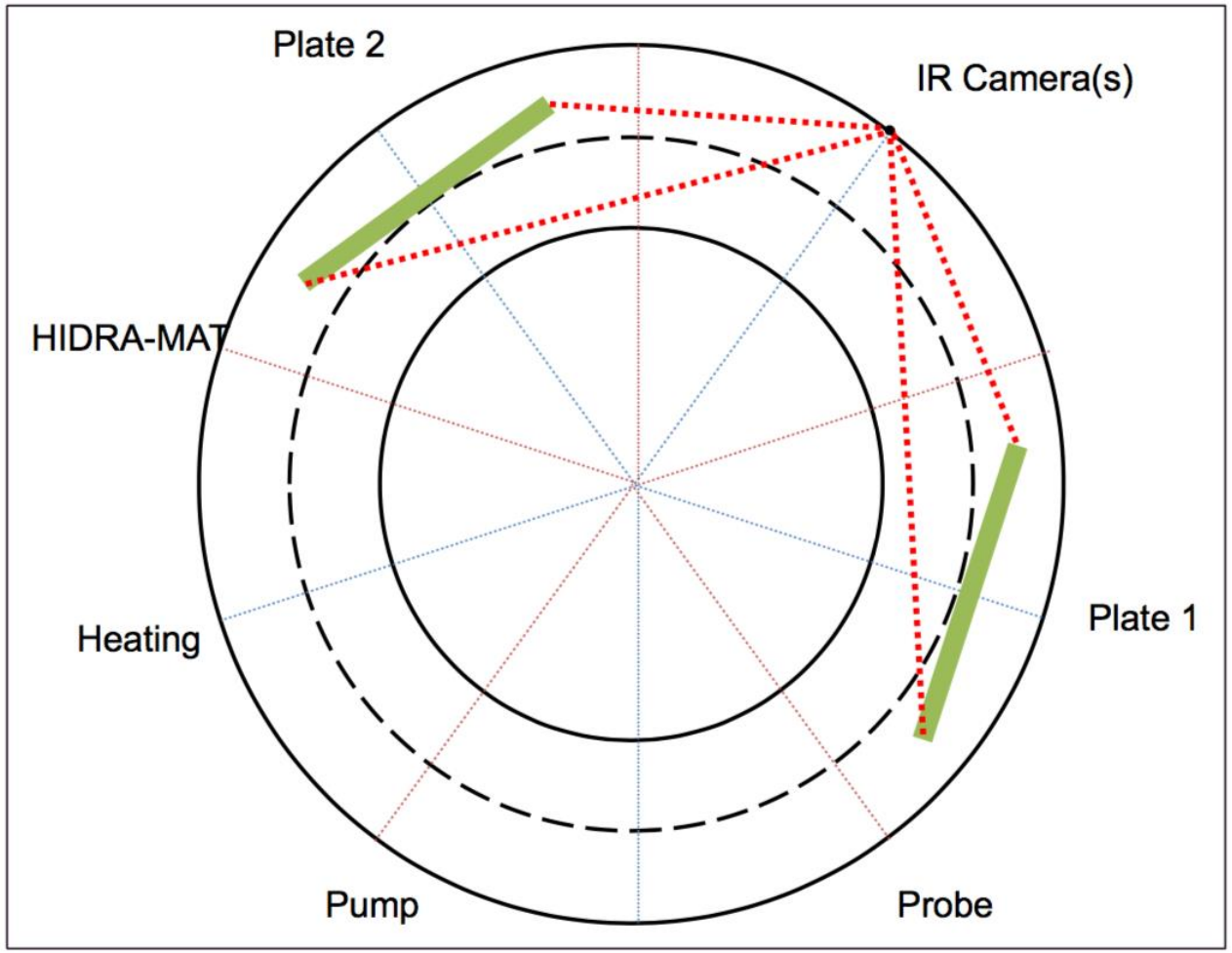
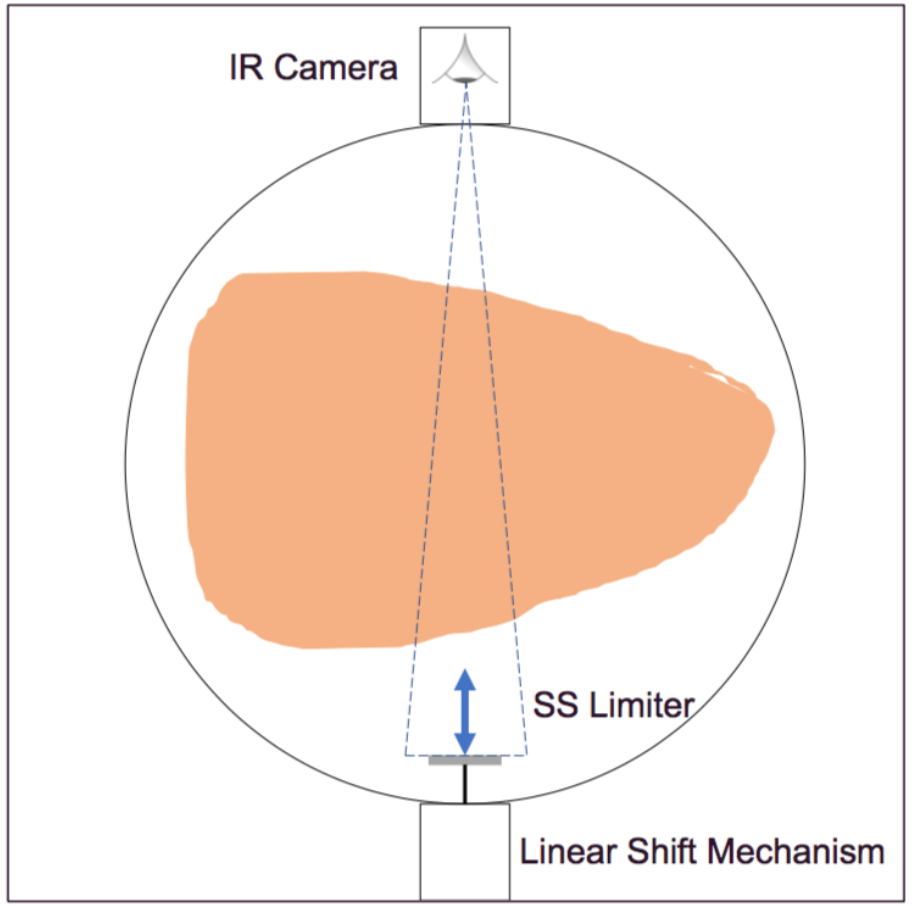
New Diagnostics for PFC visualization



(Above) Top view of planned HIDRA setup for experimental comparison between

(Below) Poloidal cross-section of planned setup for measuring radial heat flux profiles



HIDRA Diagnostics

IR Cameras

- FLIR A35sc (320×256, 60Hz)
- Two cameras allow simultaneous viewing of both flowing lithium systems
- One camera can be used with thin SS limiter to measure radial heat fluxes

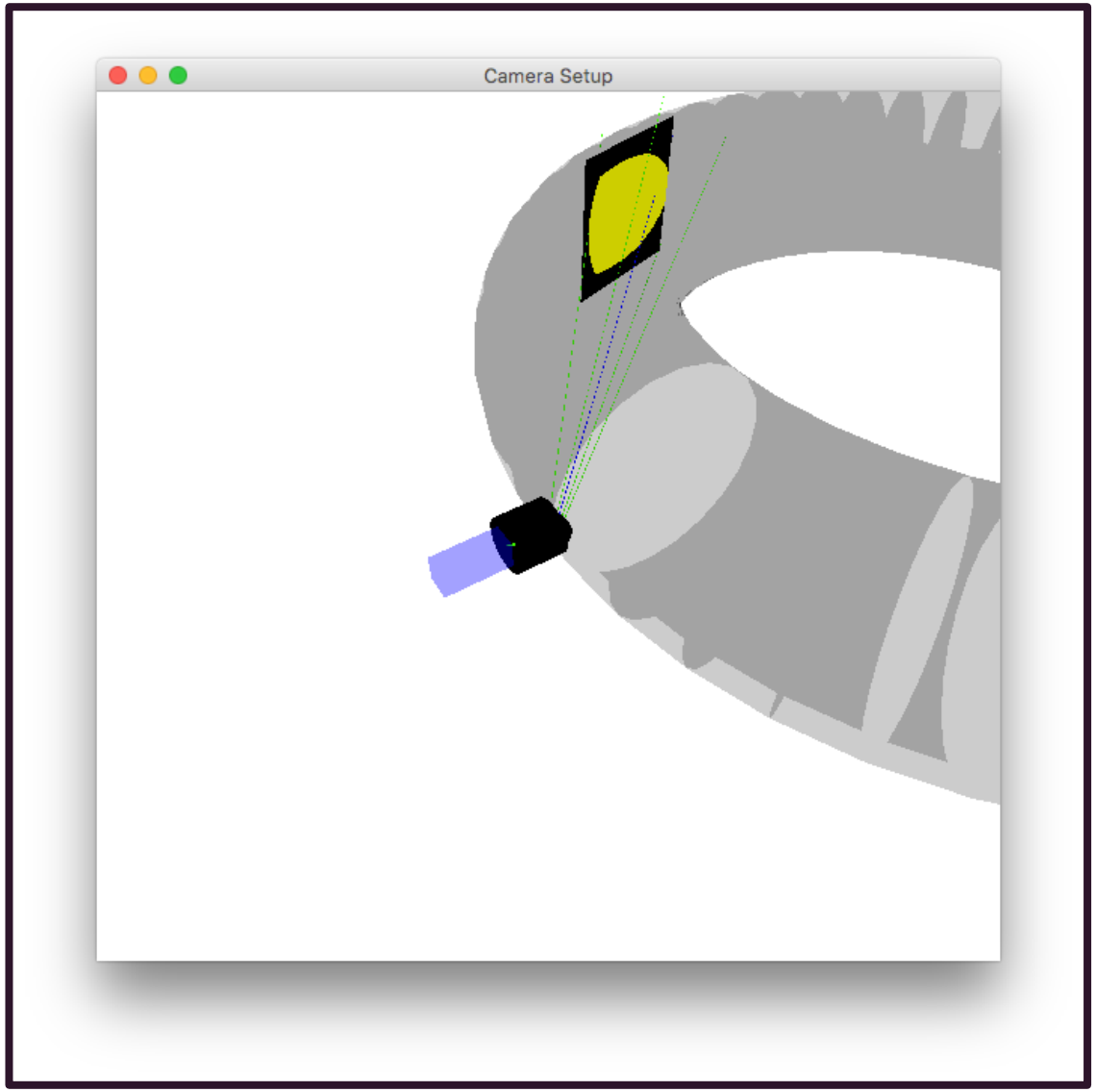
Optical Spectrometers

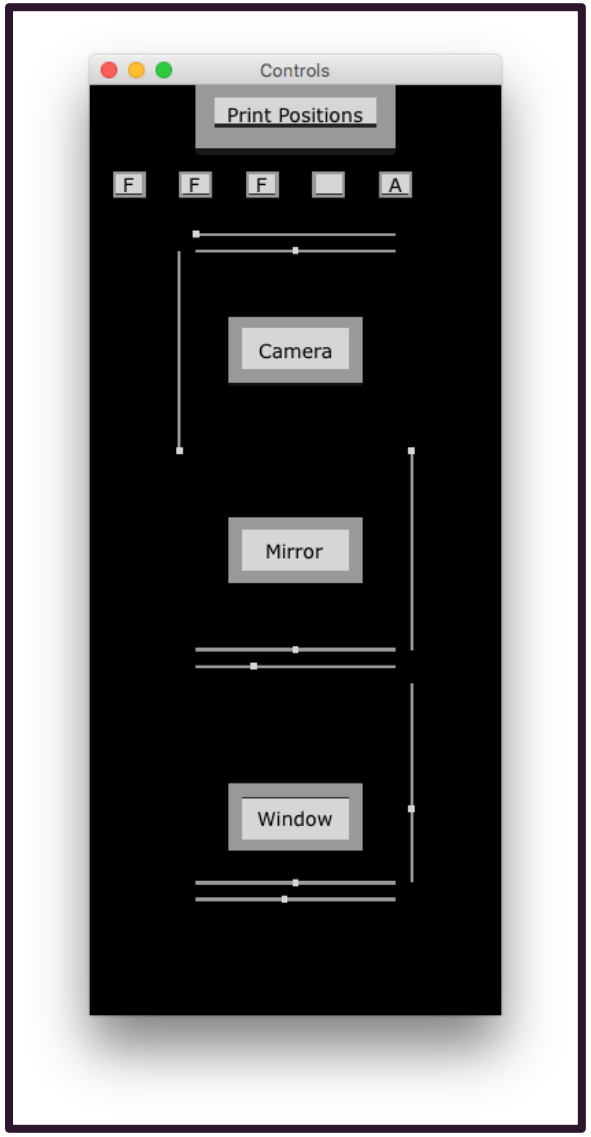
- Ocean Optics
  - H_a 630-680 nm HR2000+
  - Broad Spectrum
    200-1100 nm HR2000+ES
- E-ports directly below plates measure H, Li across surface

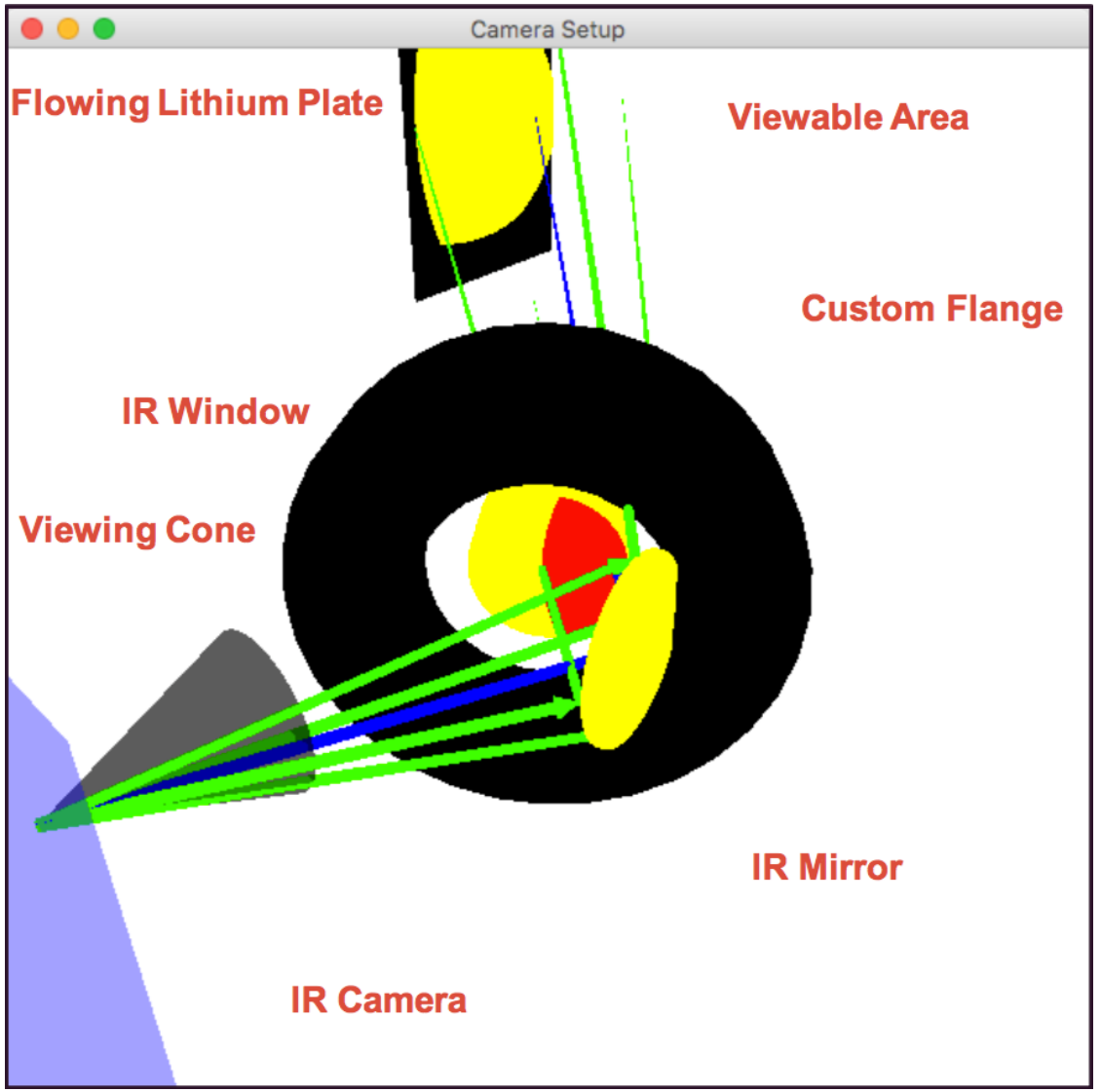
Visualization Program Used to Determine Position of IR Diagnostic

- Visual-Python script allows user to vary the
  - Position and tilt of the camera
  - Position and tilt of the IR mirror
  - Position and tilt of the IR window

- Projects the viewing area onto the plate where liquid lithium will be flowing down the surface




Controls
Print Positions
F
F
F
A
Camera
Mirror
Window


Camera Setup
Flowing Lithium Plate
Viewable Area
Custom Flange
IR Window
Viewing Cone
IR Mirror
IR Camera

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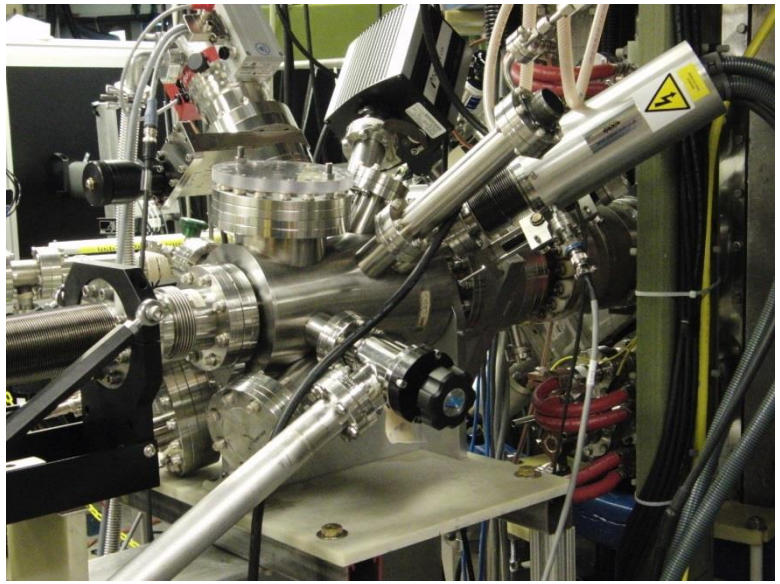
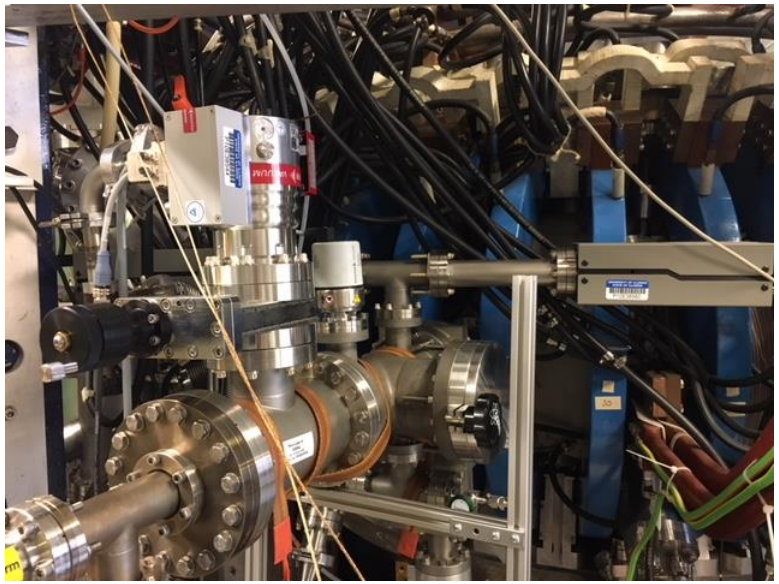
Materials Analysis Tool: HIDRA–MAT



Left: The MAPP facility installed on LTX at PPPL and will be put on NSTX-U. The HIDRA-MAT facility will be similar to this for material studies on HIDRA. This is an in-situ facility with XPS, TDS and DRS diagnostics to do surface analysis.

Right: The current HIDRA-MAT device that is being built at UIUC. HIDRA-MAT will work similarly to MAPP where material samples will be exposed to a plasma and *in-situ* measurements will allow temporal measurements of the material surface evolution.

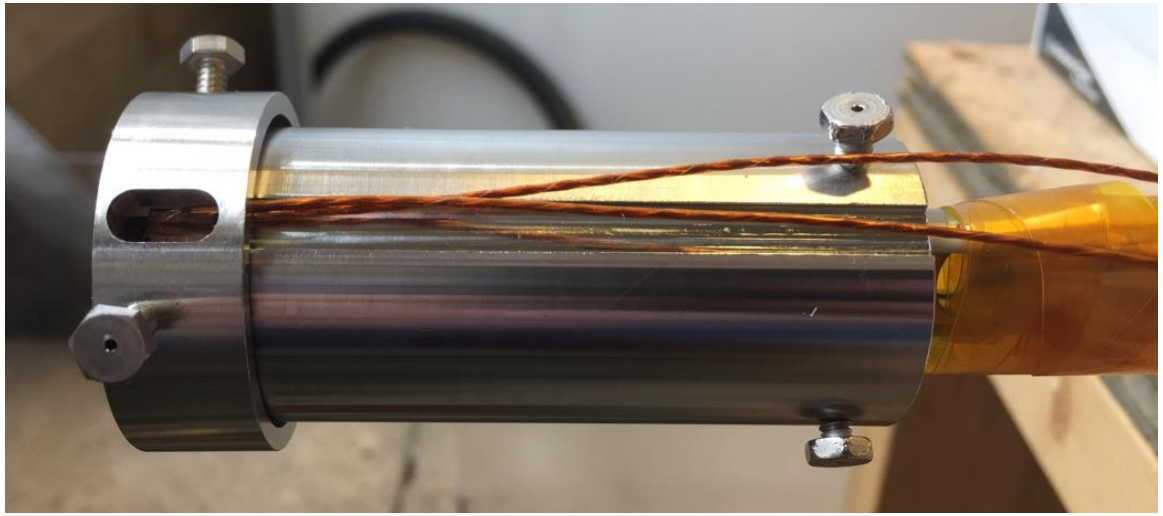


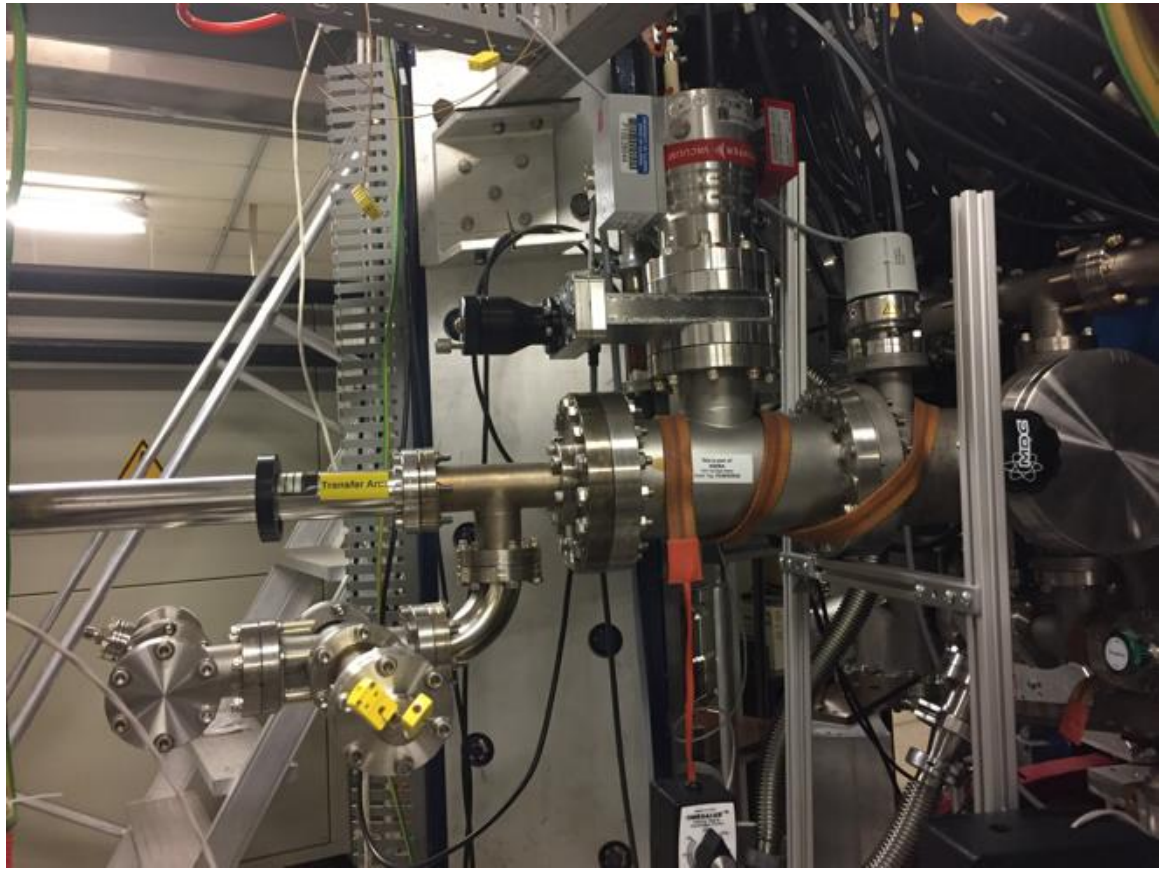
- HIDRA-MAT *in-situ* PMI facility
  - Conduct material testing experiments
  - Based on MAPP facility at PPPL
  - Turbulence and PMI effects
- Materials development
  - Test various approaches
  - Issues with operational temperature
  - Hydrogen retention
- Plasma edge diagnostics
  - liquid metals as the plasma material interface
  - Extensive experience with plasma diagnostics in extreme environments.
- **Establish empirical scaling to future plasma-burning devices at the plasma edge.**

Material Analysis Tool: HIDRA–MAT

- Platform to expose and test advanced material performance in a Stellarator.

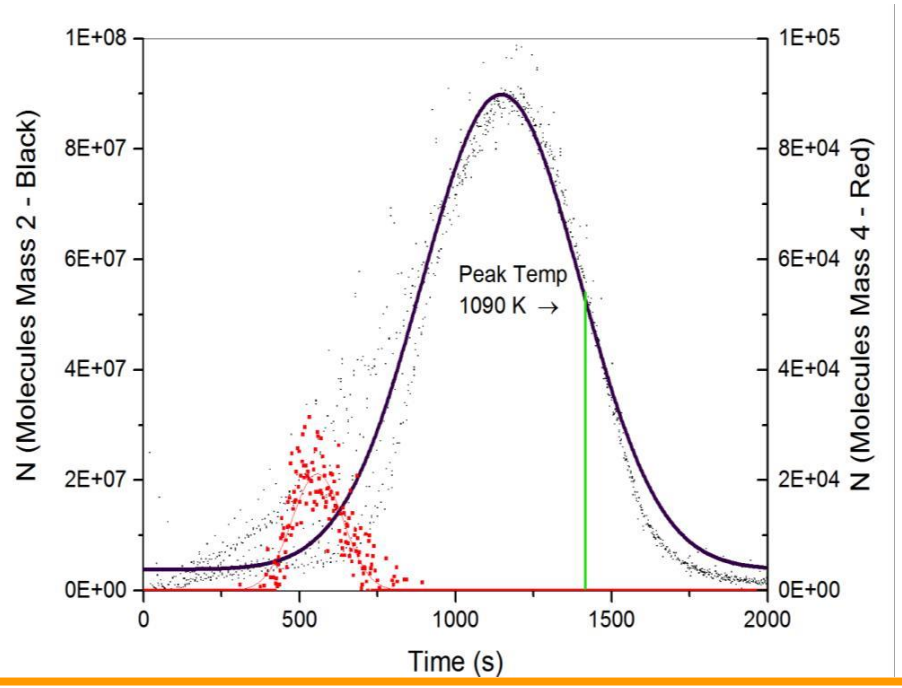
- Sample holder attached to bellows
  - Capable of linear and rotational motion allowing for precise sample positioning relative to Plasma.
  - Holder allows for sample heating up to 1200°C

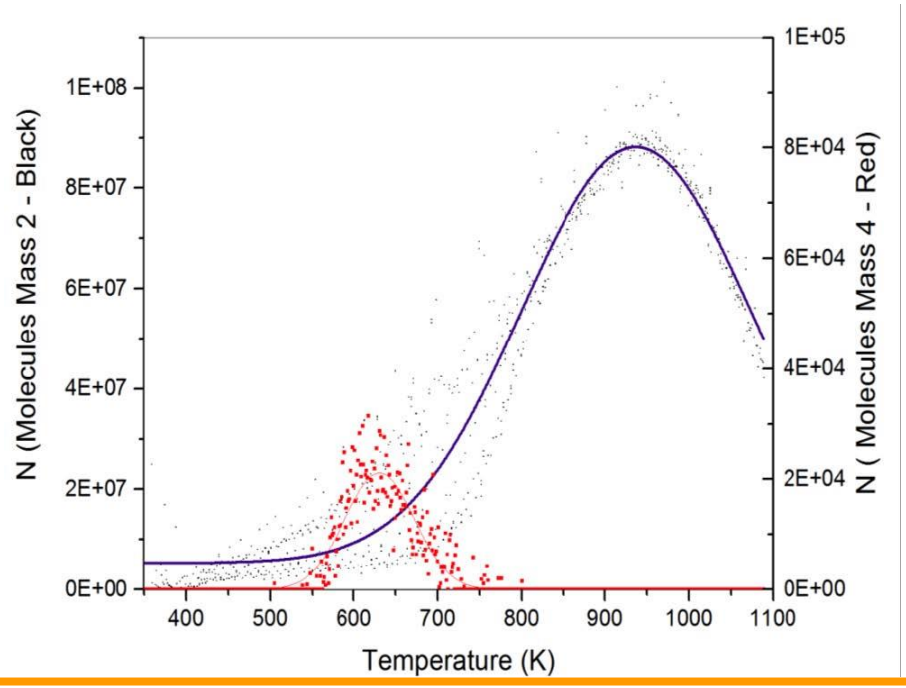




Thermal Desorption Spectroscopy

- Heater in sample holder enables TDS studies.
- Material compatibility testing with Liquid Lithium underway.
  - Complimentary to work being done at ASIPP
- Experiments have shown high H_2 retention.
  - Hindered by the inability of the RGA to distinguish between D_2 and He (due to their similar mass)
- Dual RGA system allows the ability to distinguish between D_2 and He.





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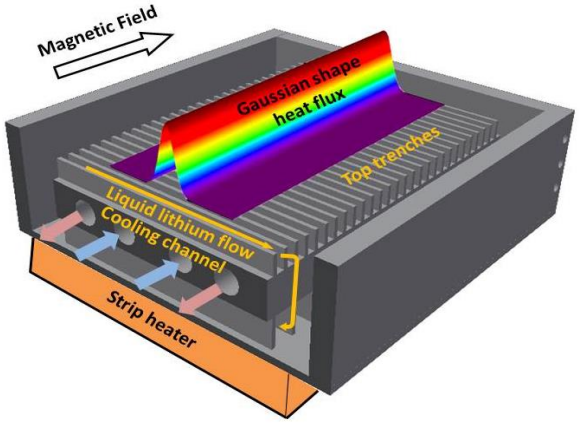
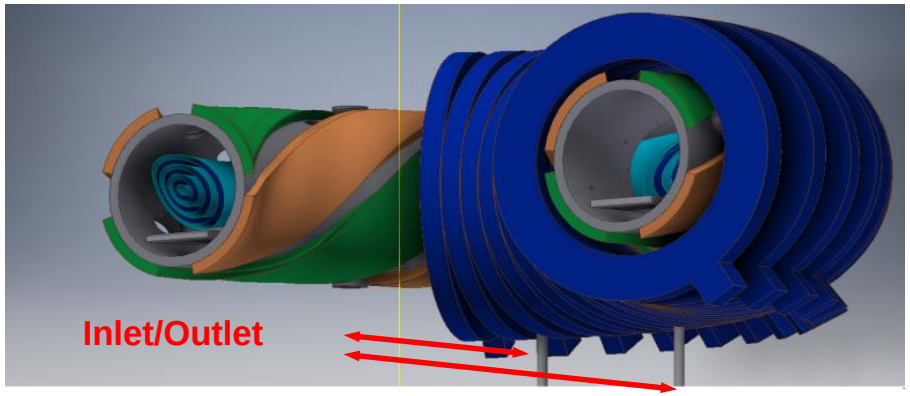
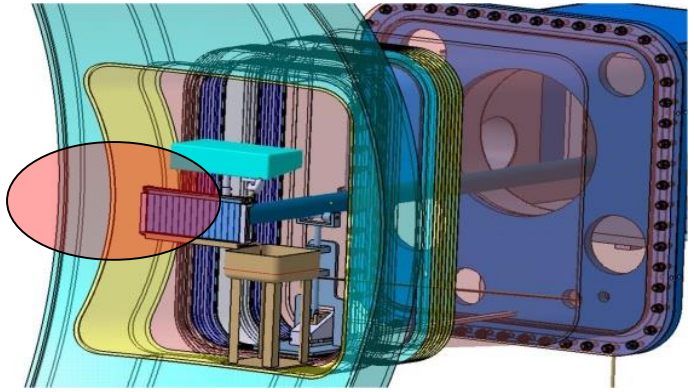
Testbed for Liquid Metal Concepts

- Important question in fusion:
  - Can a **self driven flow** work in the divertor and the first wall?
  - Will it withstand the **heat flux**?
- Answer can be provided Using HIDRA
  - $n_e = 1 \times 10^{18}$ m^{-3}
  - $T_e = 5 – 25$ eV
  - Flux outside LCFS $\Gamma = 1 \times 10^{22}$ m^{-2}s^{-1}
  - At $B_0 = 0.087$ T can get up to **60 minutes**
  - $B_0 < 0.5$ T tens of seconds.
- Flowing concepts like LiMIT, FLiLi can be tested
  - Fully toroidal
  - Island limiter/divertor concept
- Solutions for machines like EAST, NSTX-U, EAST, W7-X and future machines.

The LiMIT concept whereby a thermoelectric current is driven due to the temperature gradient induced by the plasma heat flux and toroidal magnetic field.

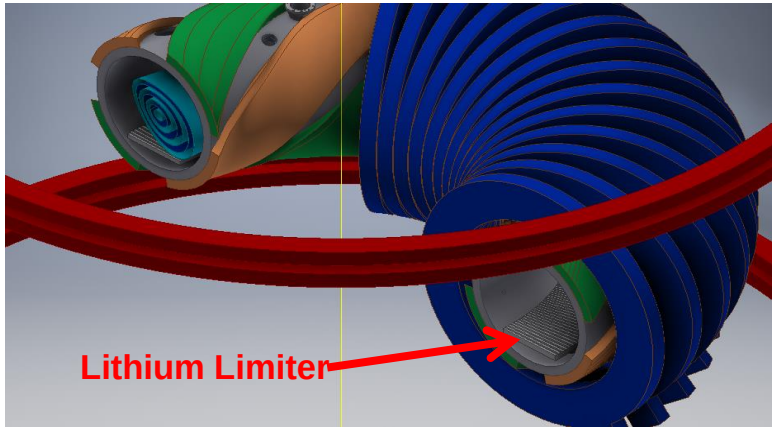






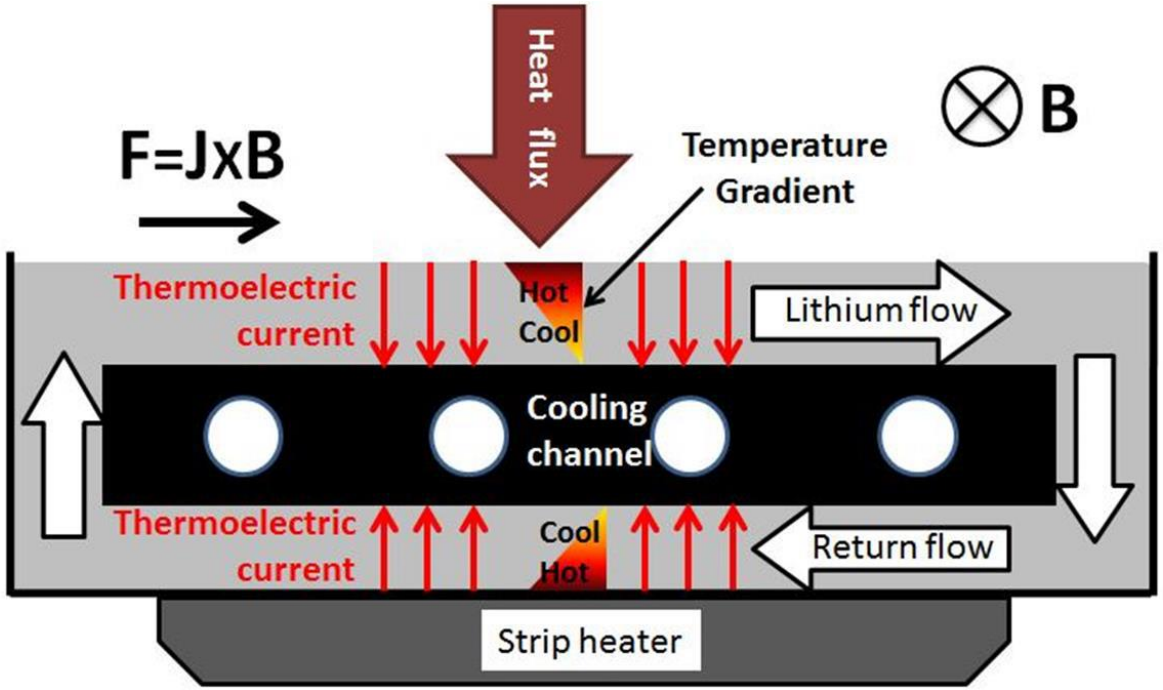
Concept of LiMIT to be installed on EAST. This will be tested mid 2019.

First conceptual design for a LiMIT limiter to be installed in HIDRA. The Liumit trenches can be seen on the bottom of the plasma vessel (below) with the inlet and outlet lines for lithium and cooling (left).



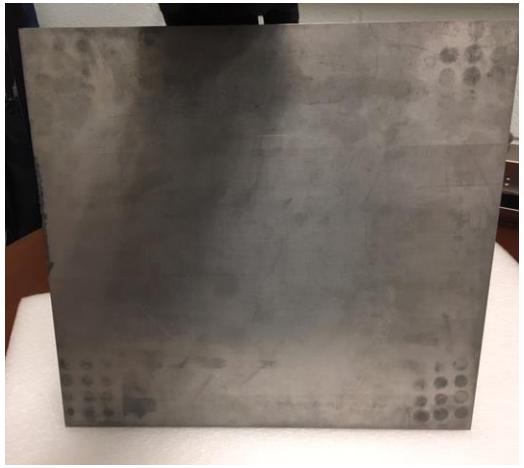
Liquid Lithium Limiters

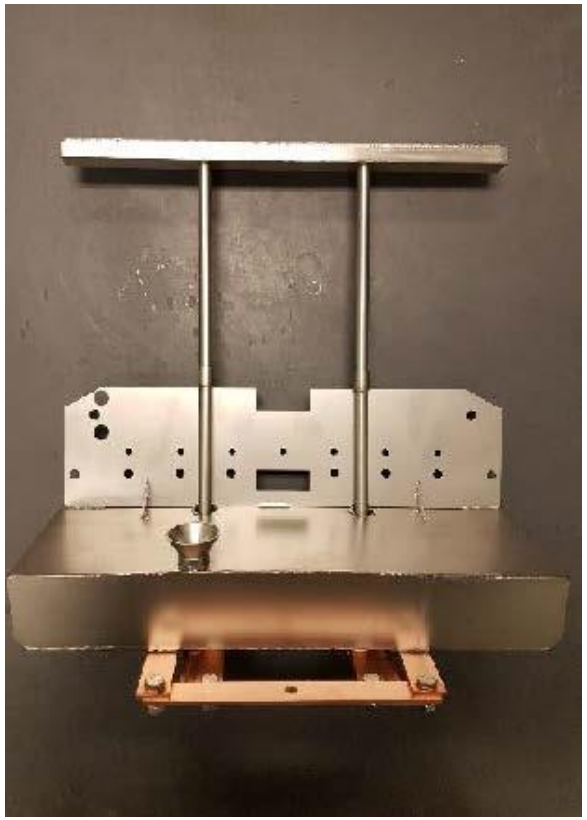
- LiMIT limiters rely on TEMHD effects.
- Thermoelectric (Seebeck) effect produced between liquid lithium and trenches if a thermal gradient is present
- If a transverse magnetic field is applied, a $\boldsymbol{J}\times\boldsymbol{B}$ force is generated the liquid will flow through the trenches.



Liquid Lithium Limiters

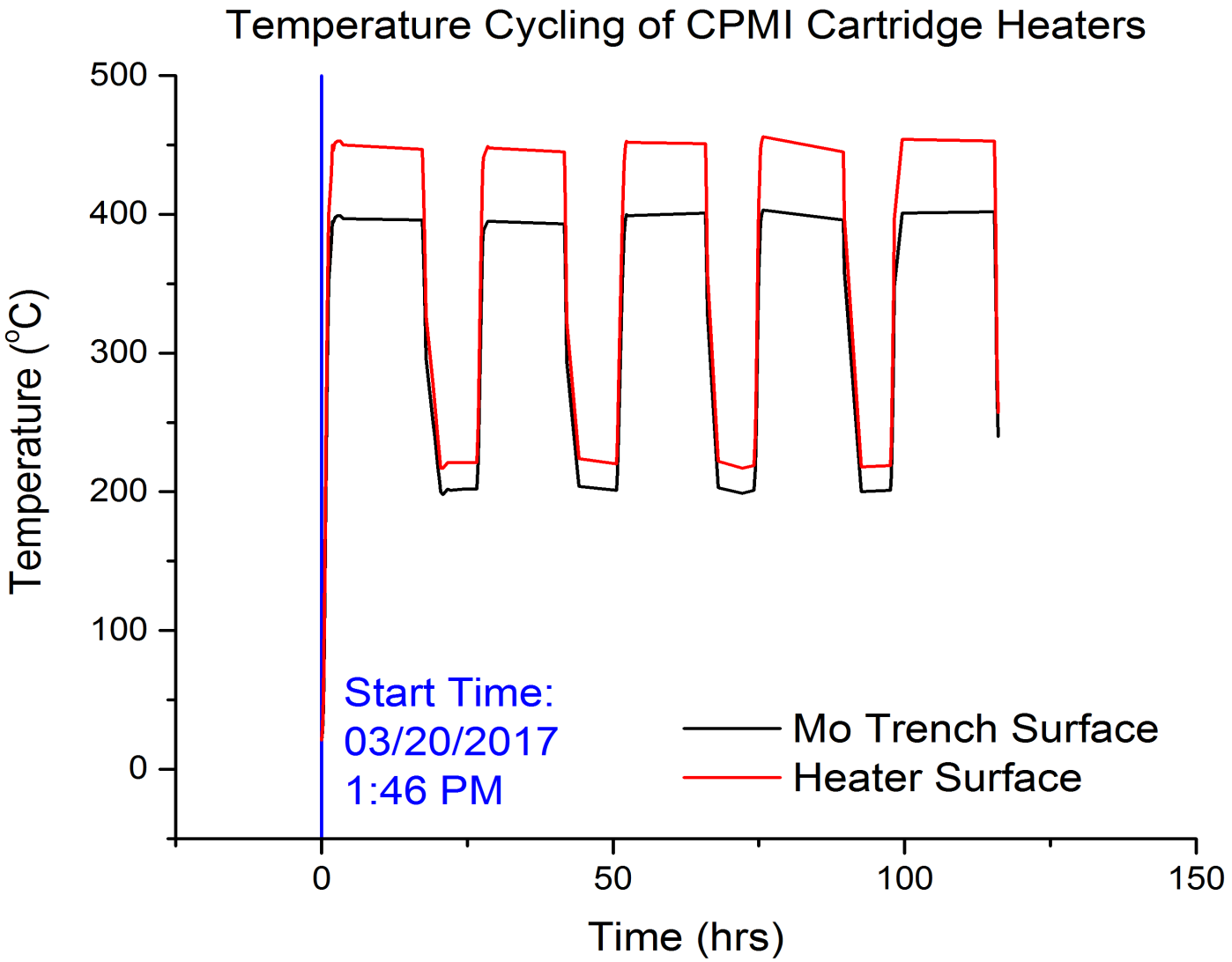
Flowing Liquid Lithium (FLiLi) Limiter





Lithium/Metal Infused Trenches (LiMIT)

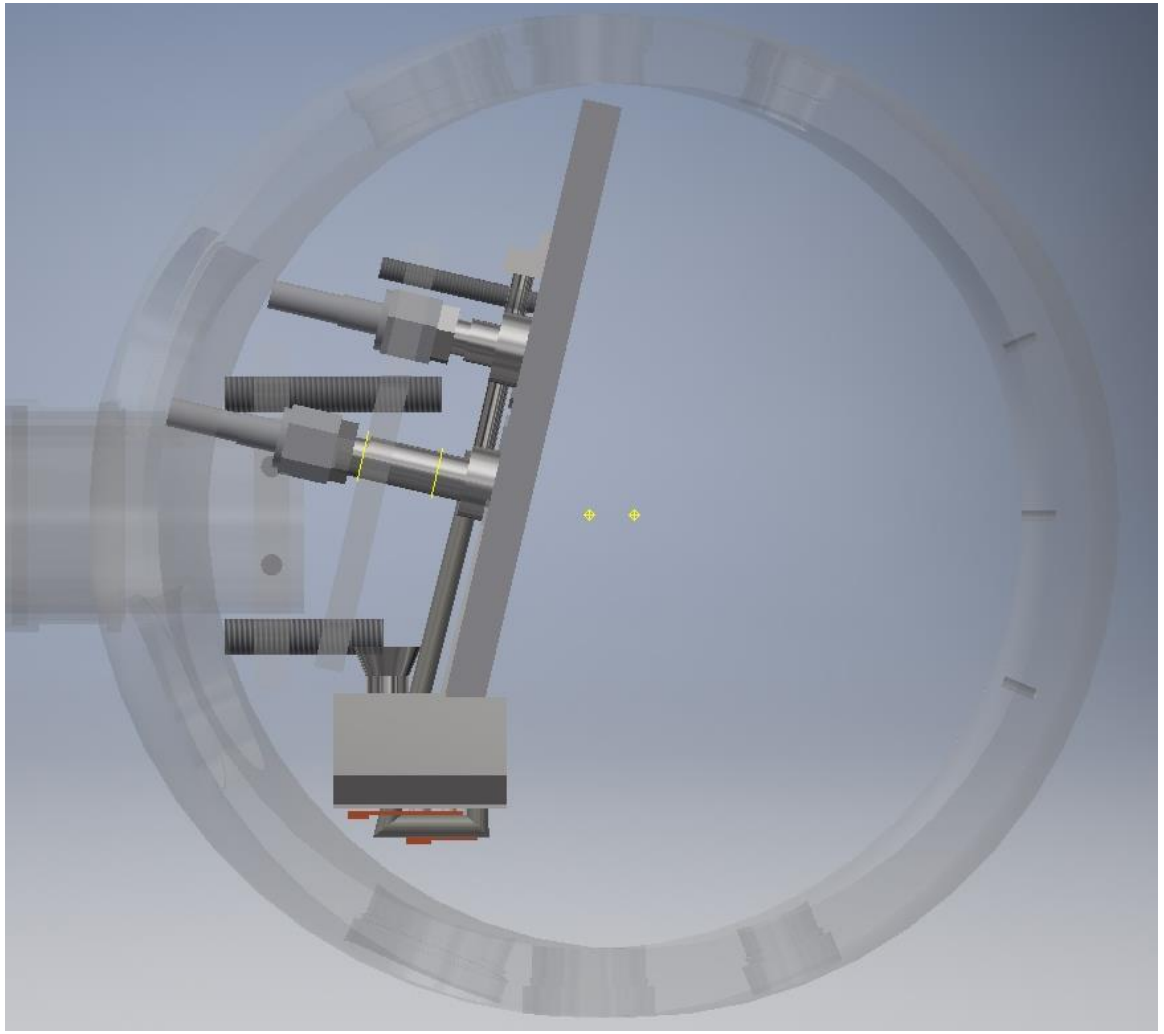
Heater Test for FLiLi



- The cartridge heaters were successfully cycled through 5 days.
- They were on average held for 14 hours for approximately 400 °C
- Then ramped down and held for approximately 200 °C on average for 8 hours
- The initial ramp up from room temperature to 400 °C on the moly plate took almost 2 hours
- The stainless steel heating plate was always about 50 °C hotter than the moly plate

FLiLi and LiMIT in HIDRA

- Testing of FLiLi and LiMIT in HIDRA
  - Aim to use limiters as a test bed of new limiter technologies before sending to EAST
  - HIDRA acts as proving ground for full scale system tests before installation onto EAST limiter arm
- Flat plate and grooved PFC test in order to take advantage of TEMHD drive
  - Designs in progress for HIDRA system testing
- Modular system for swapping the front plate independently of the collector and Li distribution system
  - Clever space utilization allows for EAST-scale system to be tested in HIDRA
  - Distributor redesign for stronger flow and less propensity for clogging



Outline

HIDRA Overview

HIDRA Control

Field Line Mapping

HIDRA Diagnostics

HIDRA-MAT

Liquid Lithium Limiters

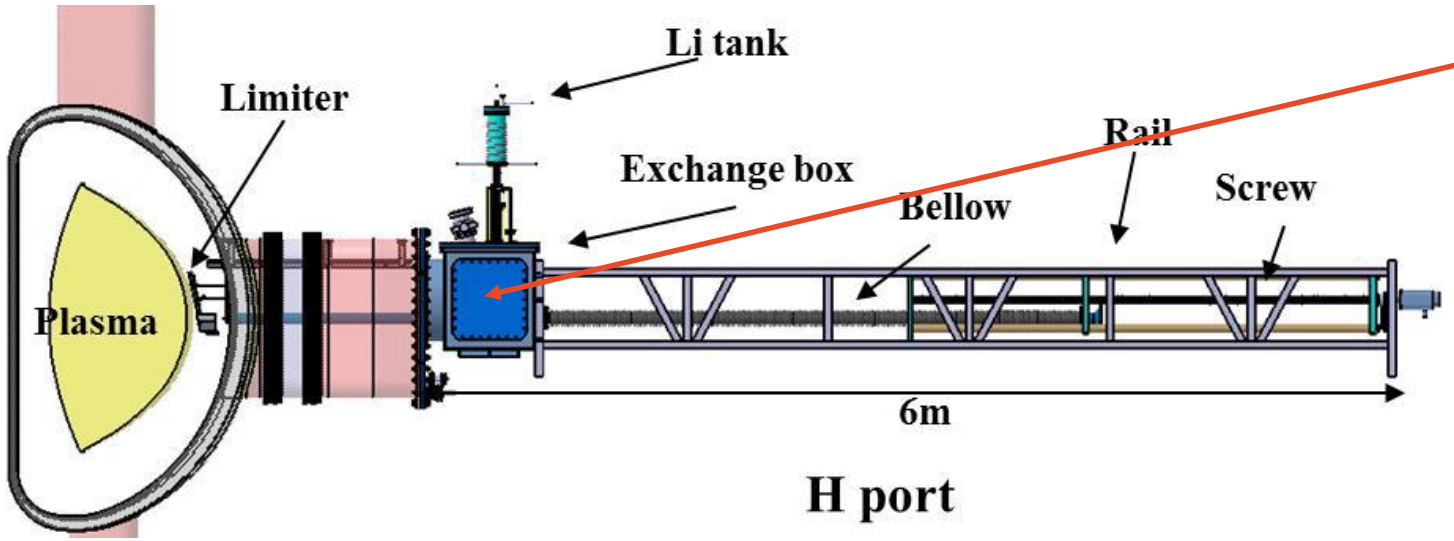
MEME

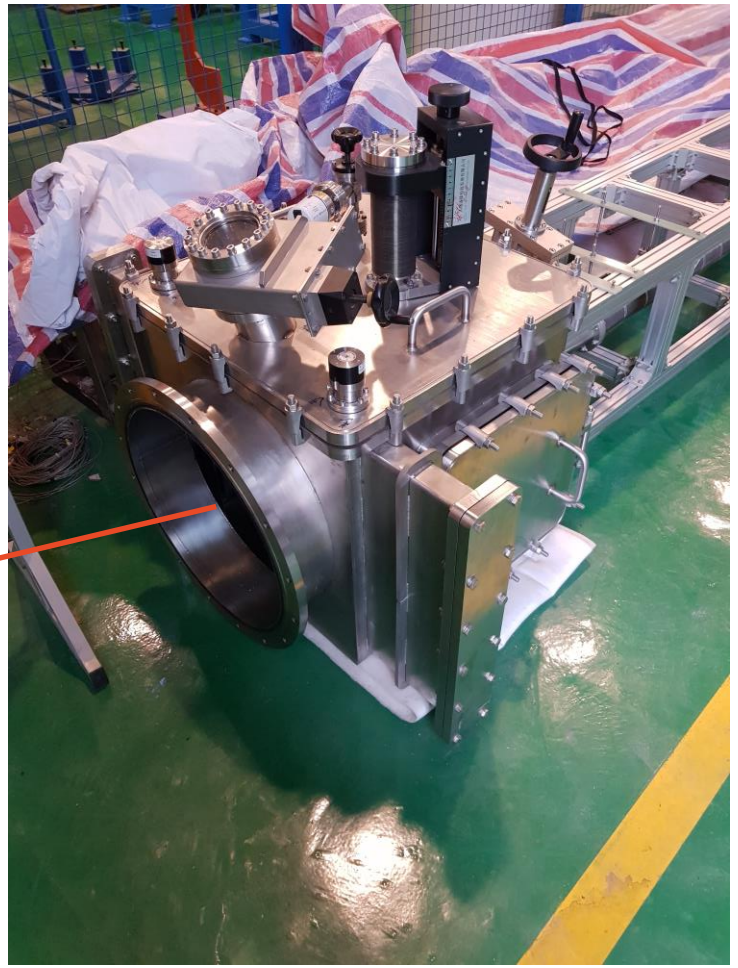
Future Work

Mock–up Entry Module for EAST – MEME

- Mock-up of the entry module for limiter insertion on EAST.

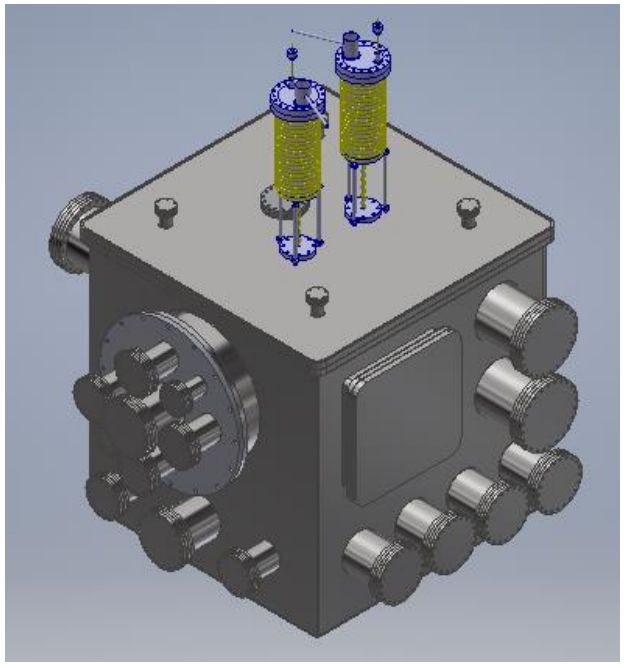
- Allows for new limiter technologies to be tailored for EAST.
  - Will be housed at UIUC and utilized to provide plug and play components for ASIPP

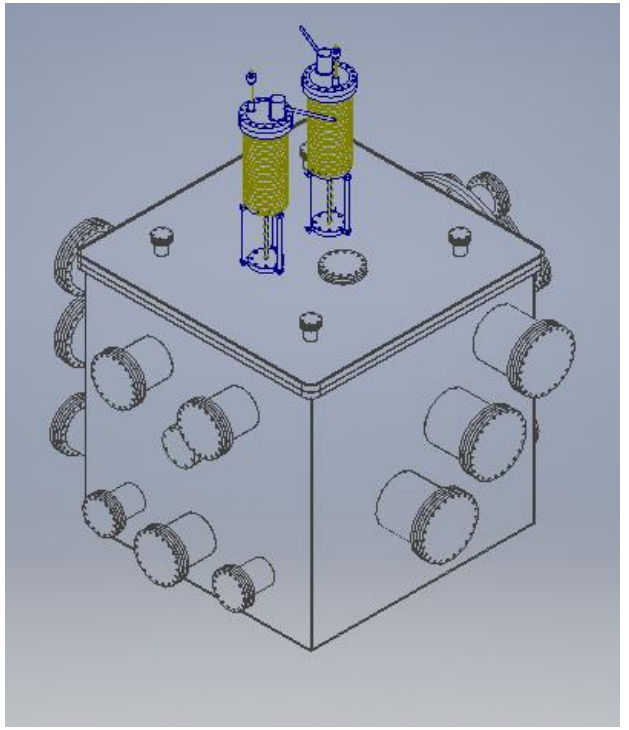




Mock-up Entry Module for EAST – MEME

- Design is slightly larger than the LiPES system.
  - LiPES components kept in relevant positions for EAST testing
- This allows for further concept testing and development to occur.
  - Future plans to widen studies into Lithium Loops, Liquid Metal divertor concept testing and materials testing





Outline

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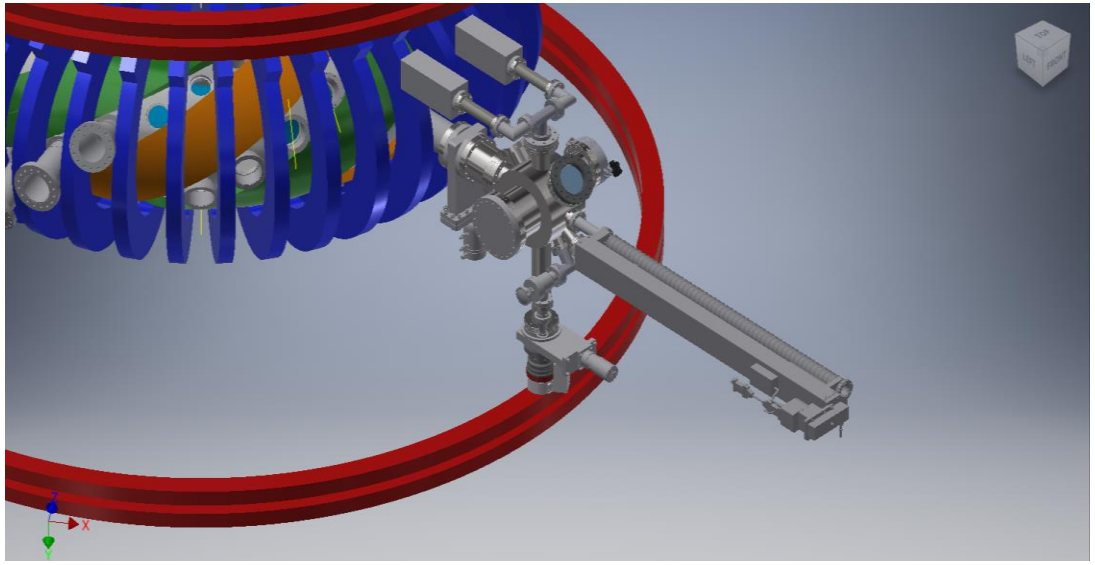
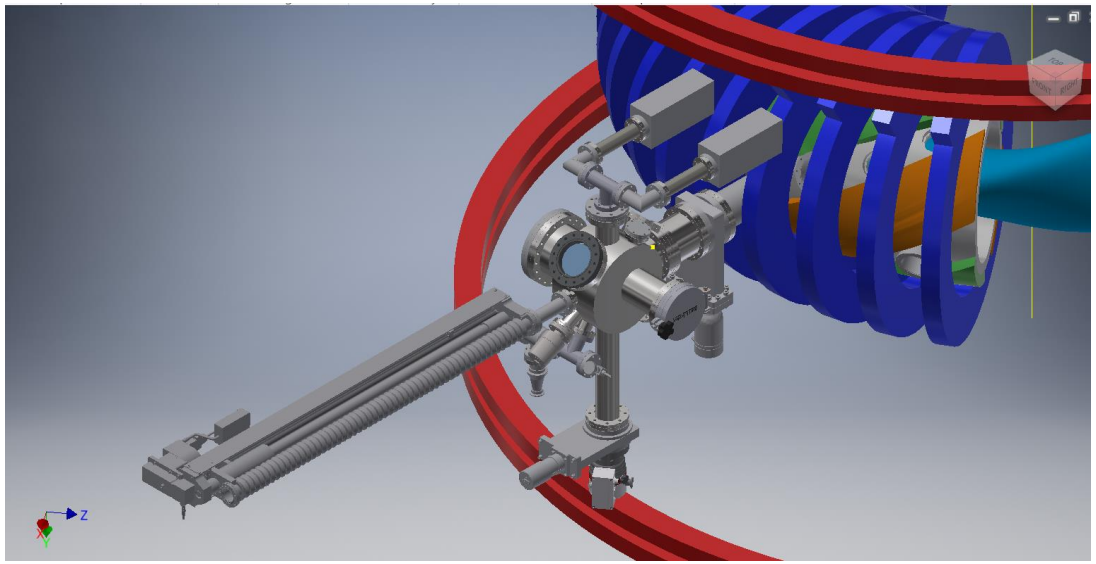
Future Work

HIDRA–MAT Redesign

- HIDRA-MAT is being redesigned to distinguish between He and D_2.

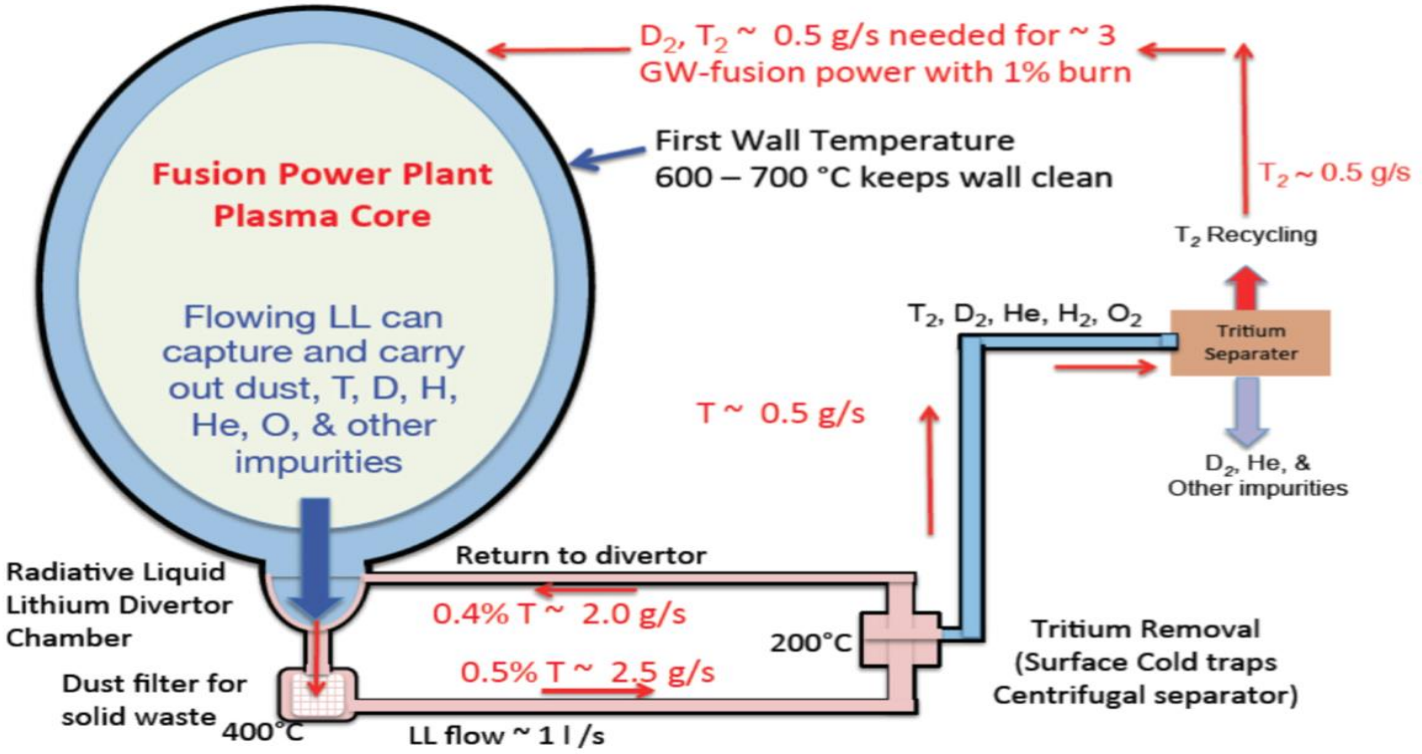
- Two RGAs attached to the chamber will have electron energies of 20eV and 50eV
  - 20 eV RGA will be able to measure H_2 and D_2 but not He
  - 50 eV RGA will be able to measure all three
  - Comparison of the two signals will allow for the He release to be calculated.





Lithium Loops and Divertors

- After successful limiter tests in HIDRA. The next step is to use a full lithium loop device within HIDRA.
  - Collector housed outside of vacuum vessel protecting it from damage from the Plasma
- Also plans to begin conceptual designs of liquid lithium divertors.
  - Have the ability to do heat strike testing using either HIDRA or MEME



M. Nieto, *et al.*, J. Nucl. Mater. **350** (2006) 101
M. Ono, *et al.*, Nucl. Fusion **57** (2017) 116056
M. Christenson, *et al.*, Nucl. Fusion **59** (2019) 026011

Summary

- HIDRA is an integral part of the PMI and PFC research and development at Illinois
  - Will be almost exclusively dedicated to PMI and PFC research which makes it unique among many fusion machines.
- PMI studies though HIDRA-MAT where not only LM system will be studied but also understand effects with edge plasmas, such as turbulence, with materials and the wall
- PFC technology development makes sure that concepts are mature and all issues resolved before installation on larger machines
  - Quick and ease shutting down and installation can mean that experiments can be installed relatively quickly compared to larger machines
- HIDRA transformer and rectifiers are fully commissioned, field mapping and heating experiments have been performed
- Diagnostics being installed as well to monitor the plasma
- Exciting future for PMI research and for plasma and fusion education ahead.

Acknowledgements

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  - College of Engineering
  - Department of Nuclear, Plasma and Radiological Engineering
  - Center for Plasma Material Interactions
  - The Office of the Vice Chancellor of Research
  - Facilities & Services at the University of Illinois at Urbana-Champaign

- Institute for Plasma Physics, Chinese Academy of Sciences

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6th International Symposium on Liquid Metal Applications for Fusion (ISLA2019)

University of Illinois, Urbana-Champaign, Illinois USA

September 30th – 3rd October 2019

ISLA2019 continues the series of symposia on liquid metal applications for fusion. Liquid lithium as well as other liquid metals will also be included in the program

The program will cover theoretical and experimental data obtained in fusion and laboratory devices, as well as technological and safety aspects of liquid metals

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Video of the Assembly of HIDRA

Time laps video of HIDRA being assembled at the University of Illinois after arriving from Max-Planck Institute for Plasma Physics, Greifswald Germany